

Conference Proceedings



1st International Conference on New Horizons in Green Civil Engineering

April 25 – 27, 2018, Victoria, British Columbia, Canada

Editor: Phalguni Mukhopadhyaya

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Foreword

This compilation of papers contains papers from the *1st International Conference on New Horizons in Green Civil Engineering* (<http://nhice.engr.uvic.ca>), held on April 25 – 27, 2018, Victoria, British Columbia, Canada. The conference was organized by the University of Victoria (www.uvic.ca) and sponsored by BC Housing (www.bchousing.org).

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Development of a New Multifunctional Structural Material: High Performance Aerogel Concrete

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Abstract:

The Institute for Structural Concrete (ISC) at the University of Duisburg-Essen developed in cooperation with the Institute of Materials Research at the German Aerospace Center (DLR) a new multifunctional structural material: High Performance Aerogel Concrete (HPAC). Chief ingredient of HPAC is silica aerogel granule which is embedded in a high strength cement matrix. Aerogel Concretes described so far in the literature exhibit very low thermal conductivities of $0.06 \leq \lambda \leq 0.10$ W/(mK) and very low corresponding compressive strength of $f_{cm} \leq 2.5$ MPa. Thus far the applicability of Aerogel Concrete as a building material for load bearing walls had to be discussed. Previous attempts to achieve the compression strength of normal strength concretes ($f_{cm} \approx 20$ MPa) involved a significant rise of the thermal conductivity up to $\lambda \approx 0.55$ W/(mK), which counteracts the benefits of Aerogel Concrete in thermal insulation. The mixtures optimized by the ISC achieved thermal conductivities of $\lambda \leq 0.25$ W/(mK) at a compressive strength comparable to Normal Strength Concrete (NSC). Compared to previous investigations, the thermal conductivities were considerable less over the full spectrum of investigated compressive strength in the range $2 \text{ MPa} \leq f_{cm} \leq 25 \text{ MPa}$. Beyond this improved correlation between compression strength and thermal conductivity, HPAC shows some remarkable properties that make it a real multifunctional structural material: By means of pull-out tests the general suitability of HPAC for reinforced construction elements was proved. Shear tests and adhesive tensile tests showed that it is possible to fabricate graded construction members made of HPAC. The building physical properties are also very promising: The measured sound absorption is higher compared to normal strength concrete. HPAC is water-repellent, open to diffusion and fireproof (melting point approx. 2000°C).

Keywords:

Aerogel Concrete, Lightweight Aggregate Concrete, (Ultra) High Performance Concrete ((U)HPC), GFRP Reinforcement, Heat Insulation.

1. Introduction

Building skins have to fulfill several requirements: They have to be load carrying, heat insulating, fire resistant, weatherproof, sound insulating and durable. Most of nowadays construction materials for outer walls don't meet all these requirements. Masonry and concrete for instance are among the most common materials for the facades of residential buildings. Such solid constructions materials usually cover the most of the above-mentioned requirements, with one exception: they suffer from poor heat insulating properties. So they have to be combined with additional layers like external thermal insulation systems which take on that task. High insulating masonry in contrast may fulfill the requirements on the heat insulating properties, but is limited in its application area due to low load carrying properties. The reason for this is that both properties, loading capacity and thermal insulating capability, depend on the dry bulk density, but correlate negatively. The ability of a construction material to meet these contradictory requirements can be evaluated by introducing a performance indicator as shown in Eq. 1:

$$P [\text{MNm}^2\text{K} / \text{Wkg}] = \frac{f [\text{MN/m}^2]}{\rho [\text{kg/m}^3] \cdot \lambda [\text{W/mK}]} \quad (\text{Eq. 1})$$

Table 1 shows the performance of some of the most common solid construction materials, which are in a range between 3.3 and $57.6 \cdot 10^{-3} \text{ MNm}^2\text{K/Wkg}$.

Table 1: Bulk densities, thermal conductivities, compressive strength and performance of selected solid materials.

Material	ρ (kg/m ³)	$f_k / f_{l,ok}$ (MPa)	λ (W/(mK))	$P_k (10^{-3})$ MNm ² K/Wkg)
Aerated Cement Block Ytong PP 1,6-0,25 [1]	250	0.8	0.07	45.7
Poroton Brick S9-MW [2]	810-900	4.6	0.09	63.1
Light-weight Concrete Block Bisoplan 14 [3]	600	2.5	0.14	29.8
Light-weight Aggregate Concrete LC35/38 [4]	1500-1600	35.0	0.89-1.00	26.2
Sand-lime Brick Silka KS-R P 20-2,0 [4]	1810-2000	10.5	0.99-1.10	5.9
Normalweight Concrete C12/15 [5]	2200-2400	12.0	1.65-2.0	3.3
Reinforced Concrete C30/37 [5]	2300-2400	30.0	2.3-2.5	5.7

It is important to emphasize that, beyond a good performance, also absolute requirements for a low thermal conductivity or high compression strength may govern the choice of a construction material. In such cases, the combination of a solid layer and a second insulating layer often is inevitable. From the application of such insulating layers, which commonly consist of EPS or XPS polystyrene or polyurethane foam, respectively, new problems may occur: growth of algae, inflammability, toxicity of fireproofing agents, insufficient recycling capabilities and so on. So it is a challenging task to develop new construction materials with a high performance that do not need additional insulating layers.

One promising approach is the so called Aerogel Concrete, where silica aerogel granule (SiO_2) is embedded in normal strength concrete matrices. Silica aerogel is an ultralight matrix material that mainly consists of air. It is among the materials with the lowest dry bulk densities and the lowest thermal conductivities. In the past, different attempts have been undertaken in order to develop Aerogel Concretes for the use in building construction. Different types of matrices (normal strength and high strength concrete) and different amounts of aerogel granule φ have been used. As can be seen from Table 2, Aerogel Concretes so far exhibit rather low performances, which is due to their low compression strength.

Table 2: Properties of Aerogel Concretes from the literature.

		Ratke 2008 [6]	Hub et al. 2013 [7]	Gao et al. 2014 [8]	Ng et al. 2015 [9]
φ	vol%	70-50	75-65	60-0	80-0
ρ	kg/m ³	580- 1050	500-620	1000- 2060	760- 2300
f_{cm}^*	MPa	0.6-1.5	1.4-2.5	8.3-62	0-149
λ	W/(mK)	0.10	0.10-0.14	0.26-1.95	0.31- 2.30
P_m^{**}	10^{-3} MNm ² K/ Wkg	9.3	25.2	13.9-28.7	21.8- 25.4

*Prisms 40 mm x 40 mm x 160 mm; **calculated with $f_{cm, cube150} = f_{cm, prism40} \cdot 0.9$

Hence, the scope of the research project described in the following [10] was the development of a High Performance Aerogel Concrete (HPAC) with an improved performance. HPAC should allow to cover all the above mentioned requirements and, in this way, the erection of residential and non-residential buildings without any further thermal insulation.

2. Mixtures for High Performance Aerogel Concretes

Far more than 100 mixtures were investigated in order to determine the influence of the mixture composition, the mixing regime and the type of storage [11, 12].

Finally, an optimized UHPC mixing composition was found, only consisting of cement, silica suspension, water, superplasticizer, organic stabilizer and aerogel granule - no sand and no coarse aggregate was added (Table 3).

Table 3: Reference mixture for High Performance Aerogel Concrete (HPAC)

Portland Cement	kg/m ³	541.0
Silica Aerogel Granule	vol%	61.4
Silica Suspension	wt%*	13.0
Superplasticizer	wt%*	3.6
Organic Stabilizer	wt%*	0.5
w/c	-	0.29

*based on amount of cement

The amount of silica aerogel granule, a commercially available, hydrophobic silicon dioxide aerogel with a particle size from 0.01 mm to 4.0 mm, a thermal conductivity of ≤ 0.02 W/(mK) and a porosity $> 90\%$, was varied in steps of 5 vol% starting at 45 vol% and ending at 80 vol%. The amount of cement and the other components were adjusted respectively. A defined mixing regime was used, resulting in self-compacting mixtures with very short setting times of about 30 minutes. Measurements of the temperature development in cube-shaped specimens with an edge length of 150 mm showed hydration temperatures up to 80 °C. The results also revealed that the hydration process was completed after about 24 hours [11]. Microsections were made of HPAC cubes in order to evaluate the structure of the hardened concrete. Figure 1 clearly shows the homogenous distribution and the complete embedding of the aerogel particles in the UHPC matrix. Since there are no organic components in HPAC, the hardened concrete can be recycled completely unproblematic.

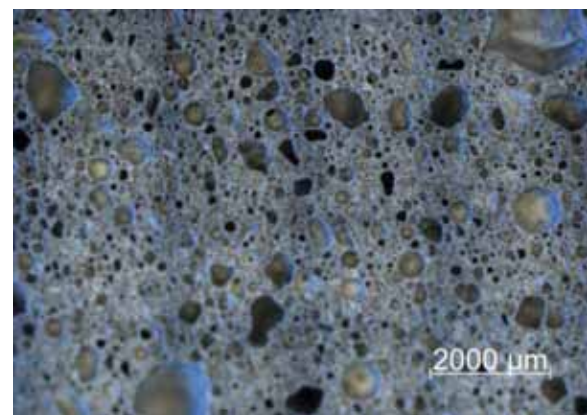


Fig. 1: Microsection of a HPAC specimen

3. Building physical properties

3.1 Thermal Conductivity

To measure the thermal conductivity several methods are available. Depending on the nature of the material and its insulation performance a suitable method was chosen. For Aerogel Concrete the Heat Flow Meter (HFM) apparatus (NETZSCH, HFM 436 Lambda) was used to take care on the inhomogeneity of the composite material.

The general measuring method [13-15] is based on the one-dimensional Fourier-Biot law:

$$\alpha = -\lambda \left(\frac{\Delta\theta}{s} \right) \quad (\text{Eq. 2})$$

where α is the measured heat flux density through the sample [W/m^2], λ is the sample thermal conductivity [$\text{W}/(\text{m K})$], $\Delta\theta$ is temperature gradient [K] and s is the sample thickness [m] measured by the apparatus.

The specific heat flow over the center measurement area A_m [m^2] is measured, thus the thermal resistance and therefore the thermal conductivity can be determined following:

$$R = \frac{\Delta\theta}{\alpha} A_m \quad (\text{Eq. 3})$$

And finally, the thermal conductivity λ [$\text{W}/(\text{m K})$] of the material is calculated as:

$$\lambda = \frac{s}{R} \quad (\text{Eq. 4})$$

For all measurements cubic samples with 150 mm edge length and a height of 30 mm were used. The thermal conductivity was measured at four different temperatures, 20°C, 40°C, 60°C and 80°C with a constant gradient of 20K. All values are listed in Table 4.

Table 4: Thermal conductivity of several samples with rising content of aerogel at different temperatures.

Mixture	M7.3	M7.5	M7.6	M7.8	M7.9	M7.10
ϕ [vol%]	54.6	60.1	62.6	70.0	75.0	77.1
$\lambda_{(20^\circ\text{C})}$ [W/(mK)]	0.255	0.191	0.212	0.137	0.108	0.082
$\lambda_{(40^\circ\text{C})}$ [W/(mK)]	0.269	0.201	0.220	0.144	0.115	0.088
$\lambda_{(60^\circ\text{C})}$ [W/(mK)]	0.277	0.208	0.227	0.152	0.123	0.095
$\lambda_{(80^\circ\text{C})}$ [W/(mK)]	0.280	0.211	0.234	0.159	0.134	0.107

As expected the thermal conductivity is in negative correlation to the aerogel content of the samples.

3.2 Sound Absorption

Preliminary test to calculate the performance of sound adsorption have been carried out with a simple self-made test unit. The apparatus follows the construction

of a tube of impedance changing from circular to square geometry. Only a rudimentary guiding value of sound transmission is received. Fig. 2 shows the apparatus.

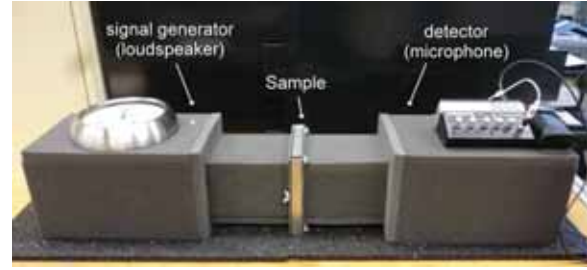


Fig. 2: Apparatus for measurement of sound transmission.

At one end of the cubic tube a loudspeaker is placed to generate a defined sound between 500 and 10,000 Hz, and at the other end a microphone is placed to measure the transmitted sound. The measurement shows a higher loss of sound transmission for Aerogel Concrete than for aerated cement or conventional concrete. These results are illustrated in Figure 3. S. Malakooti et al. [16] report on sound transmission loss on porous aerogel materials which are in the same range. For Aerogel Concrete significant higher sound transmission losses are indicated for frequencies above 4000 Hz, which are highly required to improve the building acoustic and reduce sound emission.

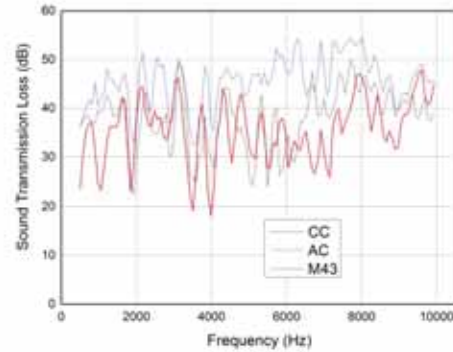


Fig. 3: Experimental Sound Transmission Loss [dB] of Aerogel Concrete sample (M43) in comparison with aerated cement (AC) and conventional concretes (CC) with a thickness of 19 mm.

We assume that the sound transmission loss and a coefficient of adsorptions μ can be predicted by the law of Lambert-Beer:

$$\mu = -\left(\frac{\ln\left(\frac{I}{I_0}\right)}{t} \right) \quad (\text{Eq. 5})$$

And within the intensities [dB], the initial I_0 and the transmitted I intensity and the thickness of the sample t [cm] a specific adsorption for the material allow the statement, that the bigger the calculated μ -value the stronger the feasibility of sound adsorption.

Exemplary the result of the measurement is shown in Table 5. It becomes obvious that the sound adsorption of HPAC is higher than that of normal strength concrete – despite of its significantly lower dry bulk density.

Table 5: Average value of μ [Hz] of High Performance Aerogel Concrete in comparison to normal strength concrete (NSC).

Mixture	M42	M51	M43	NSC
φ [vol%]	68.3	60.0	47.0	0
ρ [kg/m ³]	540	850	1340	2170
$\bar{\mu}_{(500-10.000)}$ [Hz]	0.234	0.241	0.309	0.224

3.3 Fire Resistance

Using a DLR designed set-up fire resistance tests were carried out.

A fire burner is focused on the Aerogel Concrete samples with a thickness of 30 mm. At the surface of the sample the maximum surface temperature reaches $T \approx 1000^\circ\text{C}$. The temperature at the front and back side is measured using thermal couples. In addition video images are taken for control (s. Fig. 4).

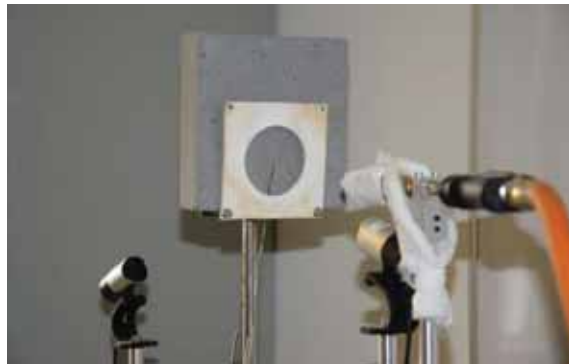


Fig. 4: Set-up for fire resistance tests.

All samples showed high resistance meaning after 90 minutes of exposure with a burner at 1000°C the backside temperature reached a maximum of 35°C .

3.4 Water Absorption and Water Vapor Diffusion Properties

The investigations on the water absorption and the water vapor diffusion properties were performed according to [17, 18]. HPAC cubes with an edge length of 150 mm were used for both test procedures. From Fig. 5 it can be seen that the range of the water absorption coefficient is about $0.015 - 0.1 \text{ kg/m}^2 \cdot \text{h}^{0.5}$, i.e. only 1%-10% of normal weight concrete ($1 - 2 \text{ kg/m}^2 \cdot \text{h}^{0.5}$, [19]). Thus, HPAC can be classified as a water repellent material what it makes suitable for the production of driving rain-resistant facades without any further protection [20]. Furthermore, it is unlikely that the low thermal conductivity of HPAC will be influenced by the water

absorption in a negative manner. A possible explanation for this behavior is the package density of the UHPC matrix and the hydrophobic properties of the used aerogel granule. From Fig. 5 it becomes obvious that the water absorption coefficient and the amount of aerogel correlate linear. Thus, it can be concluded that the density of the matrix is more dominant regarding the water absorption compared to the influence of the hydrophobic granule.

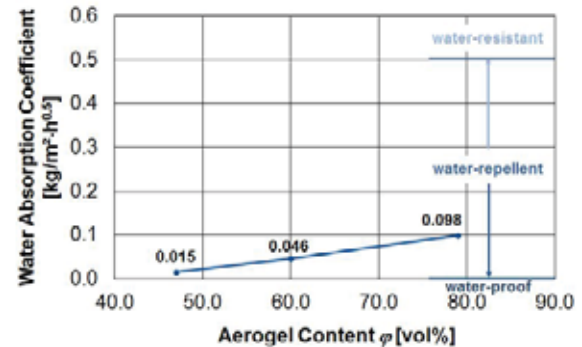


Fig. 5: Relation of aerogel amount and water absorption coefficient [21] and classification according [20]

The water vapor diffusion behavior was tested with the „dry-cup-method“, which means a gradient of relative humidity of 0% to 50%. For this test set up, the cup is filled with a drying agent, e.g. calcium chloride, and tightly covered with the HPAC specimen. The direction of the diffusion current is then from outside (50% RH) to inside (0% RH). The water vapor diffusion coefficient can be calculated by the determination of the mass gain of the specimens. Fig. 6 shows the results for different aerogel contents.

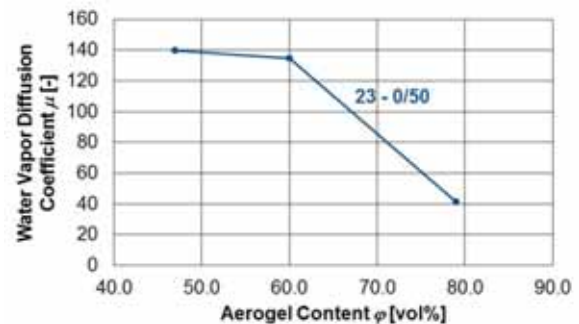


Fig. 6: Relation of aerogel content and water vapor diffusion coefficient at an ambient temperature of 23°C [21]

The values correlate negative with the aerogel content and, thus, are in good agreement with the results from the water absorption test: The lower the aerogel amount, the denser the material and the higher the diffusion resistance. The vapor transmission coefficients are comparable with the values for normal weight concrete and lightweight aggregate concrete [4] and are ranging between $\mu = 41$ and $\mu = 140$. Hence, HPAC can be classified as a diffusion-impeding material [20].

To put it in a nutshell, High Performance Aerogel Concrete exhibits desirable hygrothermal properties: It

behaves as a vapor retarder regarding the diffusion and exhibits only a weak capillary absorption under exposure to water.

4. Mechanical properties

The dry bulk density of HPAC is considerable less compared to the results of previous investigations of Aerogel Concrete from the literature (Table 2, Fig. 7). A possible explanation for this is the absence of coarse aggregate and sand which results in a reduced solid content.

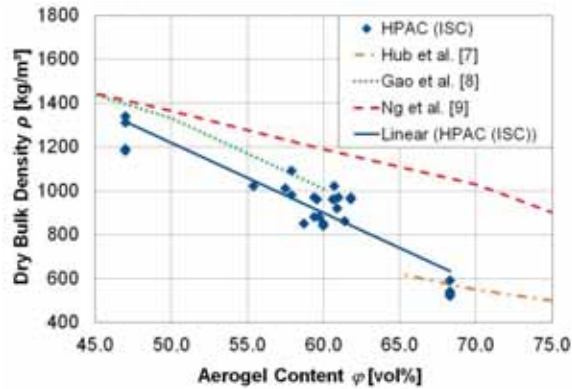


Fig. 7: Relation between aerogel amount and dry bulk density of HPAC compared to Aerogel Concrete

The compression strength was determined according to German standard [22], using both cubes with 150 mm edge length and standard cylinders 300 mm x 150 mm. The tests were performed on a universal two-pillar testing machine with a maximum capacity of 3 MN. The loading speed of 0.4 N/mm²s (± 9 kN/s) was kept by use of an electronic controlling system. Fig. 8 shows the relation between the dry bulk density and the compression strength of HPAC cubes with an edge length of 150 mm. It can clearly be seen that the compression strength is significantly higher compared to conventional Aerogel Concrete.

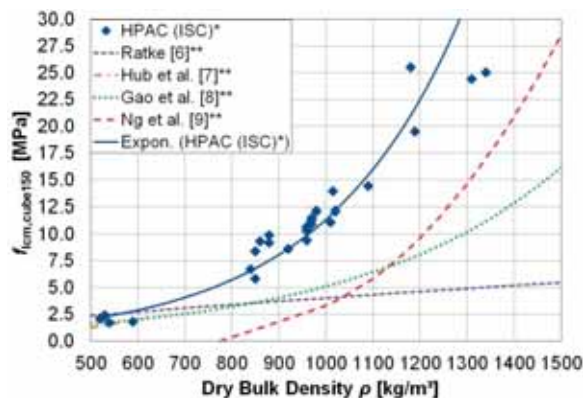


Fig. 8: Relation between dry bulk density and compression strength of HPAC compared to Aerogel Concrete (* $f_{1cm,cube150}$, ** $f_{1cm,prism40} \cdot 0.9$)

5. Results and discussions

The investigations on the physical and the mechanical properties of HPAC show very promising results. The lower dry bulk density, the higher compression strength and the lower thermal conductivities result in an improved performance of HPAC. Table 6 shows the performance of selected HPAC mixtures. It can be seen that it is two or three times as big as the performance of Aerogel Concretes known so far ($P = 9.3 - 28.7 \cdot 10^{-3}$ MNm²K/Wkg, Table 2) and higher than that of conventional wall-building materials, for the most mixtures even higher than high-insulating masonry blocks ($P = 3.3 - 57.6 \cdot 10^{-3}$ MNm²K/Wkg, Table 1). This is the reason why the new material is classified as “High Performance Aerogel Concrete”.

Table 6: Performance of selected HPAC mixtures

Mixture	M43	M7.3	M7.5	M7.6	M7.8
ϕ [vol%]	47	54.6	60.1	62.6	70
ρ [kg/m³]	1340.0	1325.8	1133.3	1021.9	690.4
$f_{1cm,cube150}$ [MPa]	25.0	25.97	16.81	10.55	4.79
λ_{RT} [W/(mK)]	0.260	0.255	0.191	0.212	0.137
P [10^{-3} MNm²K/Wkg]	71.8	76.8	77.7	48.7	50.6

The improved performance can also be illustrated by the correlation between compression strength and thermal conductivity (Fig. 9). This correlation is significantly better compared to Aerogel Concretes known so far.

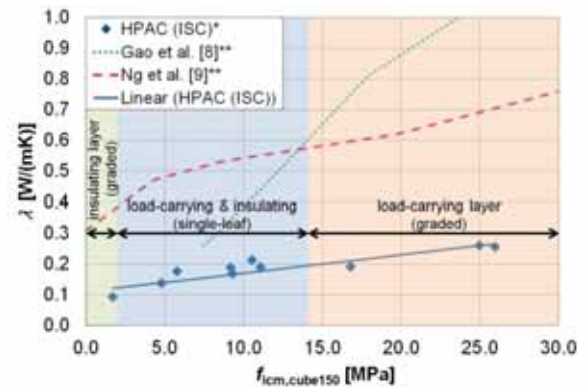


Fig. 9: Relation between compression strength and thermal conductivity of HPAC compared to Aerogel Concrete (* $f_{1cm,cube150}$, ** $f_{1cm,prism40} \cdot 0.9$)

Thus, HPAC in general is suitable for the production of load-carrying single-leaf walls without any further thermal insulation or protection against moisture. In Fig. 9, the range of possible compression strength and thermal conductivities for single leaf walls is marked. For the region of Victoria with ≤ 3000 Heating Degree Days (HDD), a single-leaf construction with a wall thickness of 50 cm would be sufficient to fulfill the requirements on the u-value according to [23]. A further

reduction of the thickness is possible using graded wall constructions. Such graded walls consist of a load-carrying and an insulating layer. Possible material combinations for graded walls are also highlighted in Fig. 9. For the example above, a combination of 12 cm load-carrying HPAC and 23 cm high insulating HPAC would be sufficient, resulting in a construction thickness of only 35 cm – still no further insulation or plaster is needed.

At the ISC, graded HPAC specimens were fabricated and tested regarding the shear strength and the adhesive tensile strength of the joint between the two layers. The specimens were made of HPAC with 50 percent by volume of aerogel ($f_{lcm, cube150} = 19.5 \text{ MPa}$) for the load-carrying layer and with 70 percent by volume of aerogel ($f_{lcm, cube150} = 2.1 \text{ MPa}$) for the insulating layer, using the fresh on solid casting method (Fig. 10).

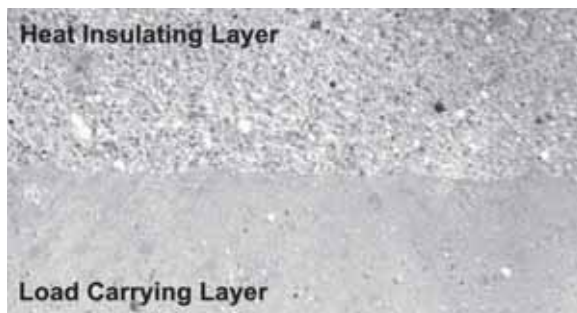


Fig. 10: Graded HPAC specimen.

The adhesive tensile strength was determined according to [24], the shear strength with the test set up depicted in Fig. 11.

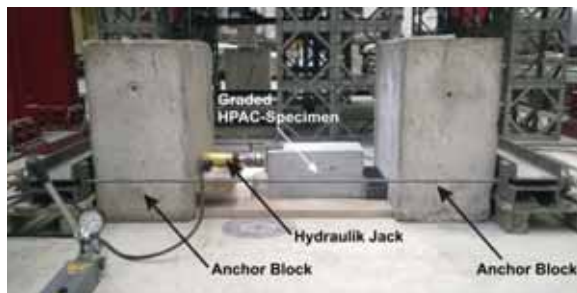


Fig. 11: Test set up for the shear tests on graded HPAC specimens.

The measured bond strength and adhesive tensile strength by far exceeded the requirements of building practice resulting from the dead load of the insulating layer and the wind suction. Thus, the general suitability of HPAC for graded construction elements was proved.

For a full applicability of HPAC instead of conventional concrete, it would be necessary to incorporate reinforcement for construction members subjected to bending. Thus, pull-out tests were performed on HPAC specimens reinforced with glass-fiber reinforced plastic (GFRP) bars. Those bars were chosen instead of steel

reinforcement in order to prevent negative effects on the insulation properties (steel: 60 W/(mK) ; GFRP: 0.5 W/(mK)) and due to the lower thermal expansion coefficient of HPAC. For the tests, specimens with dimensions of $180 \text{ mm} \times 180 \text{ mm} \times 300 \text{ mm}$ were fabricated and reinforced with GFRP bars of 12 mm or 16 mm diameter, where the bond length was 144 mm. As it is apparent from Fig. 12, the specimens were tested in a special set up mounted in a standard tensile testing machine with a load capacity of 600 kN and a displacement speed of 0.3 mm/min .



Fig. 12: Test set up for the pull-out tests.

The results showed in general the well-known bond behavior of normal strength concrete. Nevertheless, the bond stresses were slightly lower compared to conventional lightweight aggregate concrete (LWAC), but still sufficient for the production of reinforced HPAC construction members [25].

6. Conclusions and Outlook

The main focus of this investigation was the development of thermal insulating Aerogel Concrete with an improved mechanical performance to establish a new construction material for multi-story buildings with no necessity of further thermal insulation. By means of comprehensive experimental investigations High Performance Aerogel Concrete mixtures were found with a significantly increased performance in comparison to Aerogel Concretes known so far. Beside the mechanical strength, the thermal and acoustic insulation properties as well as the hygrothermal behavior the fire protection behavior of

High Performance Aerogel Concrete was proofed. Furthermore, preliminary tests were performed with regard to graded and reinforced construction members made of HPAC. All tests revealed very auspicious results. Thus, the use of HPAC for building practice is a promising option for the future.

Therefore specific standard tests have to be carried out in order to obtain the necessary general technical approval. These investigations are under progress.

A potential issue regarding the use in building practice is the currently high price of the aerogel granule which is decisive for the price of HPAC. The silica aerogel that was used for the production of HPAC so far is in a price-range around 3500 USD/m³, resulting in a price for HPAC between 1600 and 2500 USD/m³, depending on the amount of aerogel granule. New production sites for silica aerogel granule are in planning worldwide. The involved increasing production capacities will probably lead to declining prices, which are expected to stabilize at a level around 700 USD/m³. So HPAC should long term be available at prices of approximately 300-500 USD/m³. Taking into account that HPAC does not require any additional insulation or plaster, it should also become an interesting option in terms of economy.

Acknowledgements

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Mitigation of dangers caused by natural light on museum artefacts in the UAE

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Abstract:

Several studies revealed the importance of daylighting for museums. However, daylighting is not easy to control and poor indoor lighting environment could deteriorate the valuable artifacts and results in the sacrifice of visual comfort for visitors. In recent years, the UAE government has given a special consideration to conservation of its traditional buildings and turned many valuable ones into museums. Yet, these buildings were not designed or built as museums and thus concern about their performance is raised. The objective of this manuscript is to investigate the daylighting performance in traditional UAE buildings that were turned into museums with specific focus on museum lighting requirements. The study used several techniques such as on-site measurements, data collection and analysis, and computer simulation using DAYSIM (Diva plug-in for Rhino). The simulation tool was used to evaluate the lighting performance for several cases under UAE clear sky conditions. The tested climate-based daylighting metrics were daylighting autonomy, light distribution and uniformity, and light effect on artifact deterioration. The location and distribution of the sensor points depended on the size of the display room and possible locations of the artifacts. The daylighting analysis in this paper discusses four typical orientations of existing museums, which are the Northeast (NE), Northwest (NW), Southwest (SW), and Southeast (SE). Only windows in outward walls (i.e.; looking upon the streets) are examined in this paper. The results were analyzed and improvements were suggested to improve the overall lighting environment and to reduce the light exposure on the valuable artifacts. Suggestions included better spatial arrangement, better design and sizing of openings, and implementation of more effective shading systems.

Keywords:

Natural lighting, museum artefacts, preservation, UAE, lighting guidelines

1. Introduction

Traditional buildings in the United Arab Emirates (UAE) were built from local materials that were chosen to adapt to the harsh desert climate of the region. Ordinary people used simple structures like tents while houses for rulers and high status families were built from sturdier materials available at that time such as coral stones, gypsum, burnt mud (surooj), and palm trunks and fronts. After the discovery of oil in the region by the end of 1950s and the resulted boom of the economy, new buildings were constructed to accommodate the new emerging needs of the modern-transformed society. This resulted in demolishing a huge number of traditional houses and replacing them with modern buildings constructed with materials and techniques that enabled larger spatial spans with more efficient and flexible spaces. The authority later on realized the importance of these traditional houses in reflecting the country's identity, and consequently enforced laws to preserve the significant ones. Most of these buildings were converted to museums. Room spaces in these traditional houses were used as display areas for different types of display materials. Some of the highly sensitive holdings in these museums are historical documents. These are usually letters between rulers, contracts, deeds or itineraries describing pearl industry. Therefore, strict action is needed to ensure the conservation and protection of these vital documents. Nevertheless, these traditional buildings were not originally designed or built as museums and thus concern about their performance is raised. In a

previous study, the authors [1] investigated the daylight performance in a traditional museum in Al-Bastakia District in Dubai. The study found several problems in the museum spaces such as the existence of direct sunlight and high illuminance levels that could damage the artifacts and produce uncomfortable visual environment. This manuscript investigates these issues in more depth depending on survey of several case studies and the use of more detailed and accurate simulation techniques.

2. Background

Natural lighting is one of the most important aspects that need to be studied thoroughly during the design process of any building type. More importantly, daylighting in museums plays a significant role in achieving the design goals of museums. The missions of a museum are: 1- Collect and exhibit art and historic artifacts for public education and enjoyment, 2- Protect the collection from damage, 3- Do this all as efficiently as possible [2]. A museum will not be able to serve its function without both good presentation and effective preservation. The significant of daylighting in museums has many aspects. It helps to reduce the energy consumption and annual electric lighting load (thus lowering the emission of CO₂ and mitigating the greenhouse effect), ensure a positive psychological impact, ensure greater satisfaction through the artwork gratitude, and enhance the architectural experience [3-7]. However, daylighting is not easy to control and poor daylight design could result in deteriorating the exhibited

artifacts (that are usually rare and precious) and visual comfort of visitors. Moreover, light has the highest Ultraviolet (UV) radiations and thus can cause non-reversible damage to the artifacts [8, 9]. Light as a radiant energy can cause both photochemical damage (fading, yellowing, darkening of colors, loss of strength, fraying of fabrics, and even dramatic color changes of some pigments) and photomechanical damage (structural damage; surface cracking, lifting of surface layers, and loss of color) [4, 10]. The extend of this damage depends on the sensitivity of the exhibited material, the intensity of light, and the time of display. High illuminance levels, and long exposure time can accelerate the damage of the exhibited item [11-13]. Therefore, if daylight is to be allowed to penetrate into a museum, careful attention must be given to allow just the required amount of light into the space [14, 15]. One crucial way to minimize artifacts' damage caused by light is using proper light sources -following Illuminating Engineering Society of North America (IESNA) guidelines.

Annual light exposure is a metric that reports the cumulative amount of visible light incident on a point of interest, measured in Lux-Hr/year [16]. To control light exposure on sensitive artifacts when designing art galleries and museums, this metric is used with another metric that gives the maximum illuminance level that may fall on the point at any given time (i.e., max. Lux). According to IESNA Lighting Handbook and the conservation center for art and historic artifacts, the maximum illuminance limits within a display room and the recommended light exposure limits for exhibits in terms of Lux-hours per year should remain within the limits outlined in Table 1 [17, 18]. Daylight is variable over time. The illuminance in a space varies at different times of the day and year and depends on the sky conditions. Daylight analysis in museum space using the average illuminance over a period of time provides only limited value [16]. Climate-based metrics such as daylight autonomy (DA) can present a more accurate and complete picture on daylight performance over time. The standard definition of DA is the percentage of a defined period during which interior illuminance exceeds a target illumination level [17]. In this study, it is used to assess the number of hours (or percentage of time) when a particular light level is exceeded; which is useful in the case of illuminance on an artifact in a museum.

Table 1: Recommended illuminance limit and total exposure limits in terms of illuminance hours per year, adopted from IESNA Lighting Handbook [17, 18].

Type of material	Max illuminance (Lux)	Exposure time (Lux.Hrs)/ year
Highly sensitivity	50	50,000
Low sensitivity	200	100,000
No sensitivity	1000	300,000

3. Method

The study used several techniques such as on-site measurements, data collection and analysis, and computer simulation using DAYSIM (Diva plug-in for Rhino). At the outset, the research included site visits to several traditional UAE museums. In this stage the typical displays in these museums were classified and their possible locations and heights were considered. This helped to evaluate the total acceptable illuminance exposure limits based on the classification type. On-site measurements were also conducted to find the reflectance of the interior and exterior surfaces needed for simulation. The luminance meter and the Kodak grey and white cards were used to find the reflectance values of actual materials on-site. The reflectance value in Diva was generated to match that on the site as shown in Table 2. Another part of the study was data collection in which dimensions and geometry of display spaces were analyzed based on surveys of building images and architectural drawings including plans, sections, elevations and details. This analysis helped derive the needed statistical data such as the minimum, the maximum, the median, and the average values of descriptive space parameters; and a generic 3D model was created from the average measure of all descriptive parameters. These statistical data were computed for all traditional museums considered in this research. Fig. 1 shows an example of the Heritage House Museum in Dubai.

Table 2: Reflectance values of materials in the studied space.

Location	On-Site	
	Material Name	Reflectance (%)
Floor	Sand	35.7
Floor	Carpet	19
walls	(Sarooj)	86
Ceiling	Chandal Wood	29.8
Door	Chandal Wood	29.8
Window Frame	Chandal Wood	29.8
Floor	Light grey floor tiles	41.8
walls	(Sarooj)	86
Ceiling	Chandal Wood	29.8
Archs	(Sarooj)	86
Floor	pavements	20%



Fig. 1: The Heritage House, Dubai.

From the on-site visits, the typical displays in the traditional museums were classified based on their sensitivity to light as shown in Table 3.

Table 3: Types of artifacts in the UAE heritage museums.

Highly-sensitivity to light
(a) Invaluable documents and manuscripts such as letters, treaties, agreements, decrees and maps that have literally shaped the history of the country. (b) Old currency notes, stamps, and postal stationery. (c) Traditional clothing and textiles.
Low-sensitivity to light
(a) Human skeletons and bones from several excavations recovered from graves that date back to the third millennium B.C. (b) Female jewelry, some of which are prehistoric consisting mostly of bead necklaces agate, bronze, and soft stone.
No-sensitivity to light
(a) Some of the earliest coinage, silver ornaments, and costume accessories. (b) Traditional weapons including rifles, and guns; in addition to bronze daggers and arrow heads that date back to the first, second, or third millennium B.C. (c) Ceramic and basalt pottery, some of which are prehistoric consisting mostly of vessels and plates (d) Old currency coins (e) Tombs made of stone (f) Utensils made of bronze and stone

These typical exhibits were found in horizontal, vertical and sloped planes inside the display room. The current study focuses on the exhibits on horizontal planes only. The average height for the exhibits on the horizontal plane is 0.81m, measured

from the floor. In the simulation tool, a horizontal grid of sensors was created in the display room at this height to represent the artifacts displayed horizontally. The size of this grid depended on the size of the display room; which was 8m x 3m. The recommended maximum illuminance limit and light exposure limit based on the sensitivity of the artifact is taken from Table 1. Diva is used for yearly lighting calculations and time exposure measurements based on climate-based daylight metrics (CBDM). Since the aim is to ensure that display areas receive illuminance level less than the maximum level as per Table 1, the percentage of operation period that has illuminance level less than the defined illuminance level throughout the year was calculated. As mentioned previously, two main limits should be considered for preservation of artifacts; these are:

- (1) the illuminance limit (Lux)
- (2) the light exposure limit (Lux.Hrs)

When running the simulation cases, the illuminance threshold level was entered in each run depending on the material sensitivity. For example, the entered threshold level for highly sensitive artifacts was 50 Lux. The program then calculated the percentage of the number of hours per year when the illuminance is not exceeding this safety level. The second safety limit was the exposure time for these artifacts in terms of Lux-hrs. Depending on the type of the displayed material, the exposure time for the displayed artifacts was tested against the maximum limits listed in Table 1. The limits for the time exposure percentage and the exposure time for each artifact type were calculated using the following equations:

$$\text{Time exposure limit} = \frac{\text{Light exposure limit (Lux.Hr)}}{\text{Illuminance limit (Lux)}}$$

Eq. 1

$$\text{Time exposure percentage} = \frac{\text{Exposure Hours (Hr)}}{\text{Total Operatio Hours (Hr)}} \times 100$$

Eq. 2

The museums in the UAE usually operate from 8 am to 6 pm; which gives a total yearly number of operation hours equal to 3650. Many of the traditional houses used today as museums are located on coastal areas with orientations that help to promote natural cooling by ventilation using wind towers, usually the NW because of dominant desirable wind that comes from this direction. So, this explains why the building form of these buildings (usually rectangular in shape) takes the NW/SE axis and resulting in walls oriented in most cases toward NW, SE, NE, and SW. These orientations were considered in the running of the simulations. Only rooms with

windows in the outward walls (i.e; looking upon the street) were examined in this stage of the study (presented in this paper). The rooms that have windows on the courtyard (inward rooms) will be studied in a subsequent stage. The study also examined the effect of different window to wall ratios (WWR) on lighting exposure. The sensors were distributed equally inside the room, and the sensor in the middle is used to evaluate the general lighting performance and the exposure time measurements in the simulated room.

4. Results and discussions

General lighting evaluation- For the Southeast (SE) orientation, the percentage of exposure time was calculated for different WWRs for the three types of artefacts. Then, a governing equation that relates the percentage of exposure time and the WWR was derived based on the trend line of the produced data. This relationship was drawn for the three-display artefacts types which are the high-sensitive to light, the low-sensitive to light, and the no-sensitive to light materials. This helped to understand the general lighting behaviour for all exhibits.

The grid simulated results for the percentage of time exposure for different WWR in the SE orientation is shown in Fig. 2 through Fig. 4. Eq. 1 and Eq. 2 were used to calculate the limit of the time exposure percentage and the limit of exposure hours for each type of display exhibits. Generally, as the WWR increases, the percentage of safe exposure time decreases for all displayed artefacts. However, this decrease varies from one type of display exhibit to another. Another important observation is that the percentage of safe exposure time for the no-sensitive (to light) materials is higher than that for the low-sensitive materials, and the latter is higher than that for the high-sensitive materials for the same WWR. This can be referred to the fact that the illuminance limit for the high-sensitive artefacts (50 Lux) is less than that for the low-sensitive artefact's (200 Lux), and the latter is less than the illuminance limit for the no-sensitive artefacts (1000 lux).

Highly sensitive to light artefact - The limit of the percentage of safe exposure time for this material was calculated using Eq. 1 and Eq. 2 to be 27.4 % which is equivalent to around 1000 Hr of the total operation hours (3650 Hr) as shown in Fig. 2. This figure also illustrates that when WWR=5%, around 5%(182.5Hr) of the total occupied hours (3650 hrs) is safe based on illuminance limit (50 Lux). Since this 5% is less than the percentage of safe exposure time (27.4%) limit, then it is considered safe based on the light exposure limit (50,000 Lux.Hrs). The remaining percentage of occupied hours when WWR=5%, which is 95 % is the time that this type of artefacts is not safe based on illuminance limit and based on exposure time limit. It is also noticeable that the safe percentage of exposure time reduces as the WWR increases. This means that this type of artefacts

would require a lower value of WWR (< 5%) in order to be safe. Therefore, radical solution should be taken to protect this type of artefacts by separating them in a different room with no windows at all. Another solution could be to use materials with lower reflectance values for walls and ceiling to reduce the overall illuminance levels. The best data fitting equation that represents the relationship between the percentages of safe exposure time for different WWR in the SE orientation for the high-sensitive to light artefacts can be expressed as follows:

$$\text{Time exposure for H.S.} = a.WWR5 + b.WWR4 - c.WWR3 + d.WWR2 - e.WWR + f \quad \text{Eq.3}$$

Where $a = -0.0003$; $b = 0.0147$; $c = 0.2324$; $d = 1.6648$; $e = 5.4347$; $f = 8.9879$

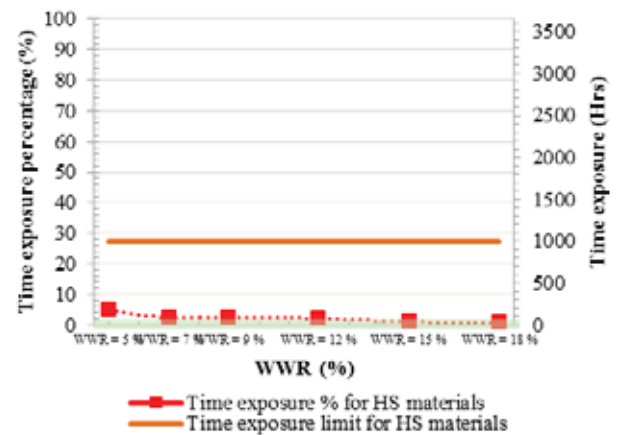


Fig. 2: Time exposure for different WWR for High-sensitive to light exhibits in the SE direction.

Low sensitive to light artefact – the limit calculated for the low-sensitive materials (as per Eq.1 and Eq. 2) is 13.7% (i.e., 500 hours of the total 3650 operation hours). Whereas Fig. 3 shows that approximately 74% of operation hours is safe based on the illuminance limit (200 Lux) when WWR was 5%, only 13.7% of the operation hours is safe based on the light exposure limit (100,000 Lux.Hrs). So, to keep the low-sensitive material safe based on both the illuminance limit and the light exposure limit, these artefacts should be exposed to a maximum of 500 Hr of the total yearly operation hours. This could be easily achieved by using sensors that control the shutters of windows and keep them open only 500 Hr throughout the year. Another solution is to use local shade trees. Previous research by Al-Sallal and Abu-Obeid [19] demonstrated that local shade trees in the UAE could reduce the overall levels of illuminance by 18–31% in classrooms oriented to north and by 87–96% in classrooms oriented to other directions. On the other hand, 26% (949 Hr) of the total operation hours when WWR=5% is not safe neither based on illuminance limit nor based on light exposure limit. Fig. 3 also shows that when the WWR=10.5%, the maximum percentage of exposure time is reached that satisfies both the illuminance and the light exposure limits for this type of artefact. Thus, it is recommended to

redesign and re-size the existing windows to reach to WWR=10.5% for display rooms oriented in the SE. This could be done by closing only a part of the window while opening another part equal to the size of the designed WWR. The best data fitting equation that represents the relationship between the percentages of safe exposure time for different WWRs in the SE orientation for the low-sensitive to light artefacts is as follows:

$$\text{Time exposure for L.S.} = g \cdot \text{WWR}^3 + h \cdot \text{WWR}^2 - i \cdot \text{WWR} + j \quad \text{Eq. 4}$$

Where $g = -0.0351$; $h = 1.4372$; $i = 19.509$; $j = 89.624$

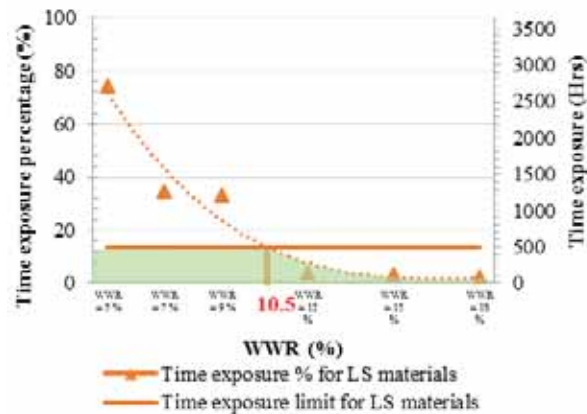


Fig. 3: Time exposure for different WWR for the low-sensitive to light exhibits in the SE direction.

No sensitivity to light materials – Fig. 4 shows that when WWR=5%, only 8.22% (300 Hr) of the total yearly operation hours (3650 Hr) is safe based on both illuminance limit (1000 Lux) and light exposure limit (300,000 Lux.Hrs); 97% (3540.5 Hr) of the total yearly operation hours is safe based on the illuminance limit (1000 Lux) only; and 3% (109.5 Hr) of the total yearly operation hours is not safe based on both limits. The results also show that the safe percentage of time exposure reduces as the WWR increase. Since the time exposure limit for this type of artefact that satisfies both limits is very low (300 Hr), it is recommended to place them in display rooms with WWR>18% to ensure that they will be safe based on both recommended limits. The best data fitting equation that represents the relationship between the percentages of safe exposure time for different WWR in the SE orientation for the no-sensitive to light artifacts is as follows:

$$\text{Time exposure for N.S.} = k \cdot \text{WWR}^2 - l \cdot \text{WWR} + m \quad \text{Eq. 5}$$

Where $k = -0.2716$; $l = 0.8523$; $m = 99.382$

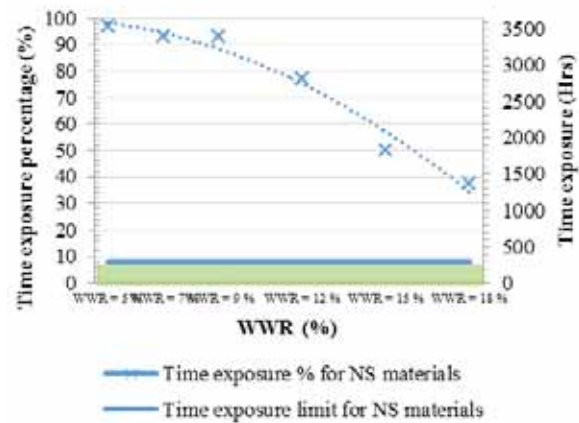


Fig. 4: Time exposure for different WWR for the no-sensitive to light exhibits in the SE direction.

5. Conclusions and outlook

The study applied different methods. The survey of architectural drawings and images assisted in extracting the needed design information for lighting performance analysis of these traditional museums. These design data analysis were used to create a representative prototype to evaluate the daylighting for different types of artefacts. Also, on-site measurements were conducted to classify the exhibited artefacts based on their light sensitivity (high-sensitive, low-sensitive, and no-sensitive). The daylighting autonomy (DA) was simulated to investigate the impact of the resulted luminous environment on each type of artefact. The most important findings can be outlined as follows:

- The high-sensitive artefacts to light showed high levels of daylighting autonomy (>97%) with a stable trend. This indicates a severe danger that requires a major solution to ensure high protection of the artefacts. Therefore, it is recommended to use separate rooms that have no windows and equipped with low-illuminance electric lighting system.
- The low sensitive artefacts are generally safer than the high sensitive ones with an average 54% DA. A recommended measure to improve their safety is to add an intelligent shading system on the façade that helps to control the direct sun and provide uniform daylight distribution.
- The no-sensitive artefact shows the least DA levels compared to the other ones. This indicates that this type is the safest based on design parameters found in the traditional UAE museums.

Acknowledgements

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Hygrothermal and structural performance of light wood frame walls with insulated sheathing

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Abstract:

In order to meet a higher standard of building energy efficiency, the thermal insulation of exterior walls is often increased. Adding a layer of continuous thermal insulation exterior to the cavity insulation, insulated sheathing, to reduce thermal bridging is getting more popular in practice. In some cases, the continuous insulation is put outer to the wood sheathing while in other cases the wood sheathing is inserted between the lumber and sheathing. The former configuration will limit the air-drying capability of wood sheathing due to the low permeability of the continuous insulation. On the other hand, the latter configuration compromises the racking resistance of the wall due to the soft foam layer inserted between lumber and wood-based panels. Clearly there are contradicting influences on thermal and structural performance of the wall when the insulation thickness changes. Moreover, the hygrothermal performance of these two construction approaches has not been fully investigated. This study aims to investigate and compare the hygrothermal and structural performance of two proposed wood-frame exterior wall configurations. The impact of the insulation thickness on shear wall resistance was investigated. Numerical simulations have been carried out to investigate the hygrothermal performance of the walls configurations under steady-state vapor diffusion. Preliminary results have shown that these two wall configurations have similar hygrothermal performance. Materials with high permeability should be used for the continuous insulation. As for structural performance, the addition of insulation thickness always reduces strength of nailed joints and therefore that of shear walls.

Keywords:

wood-frame walls, hygrothermal performance, shear wall, lateral load resistance, energy efficiency

1. Introduction

To reduce heating energy consumption, the National Building Code of Canada (NBCC) has mandated new requirements on the thermal insulation values of exterior walls for buildings. Part 9 of NBCC (NRC 2015a), which is adopted in most of the provinces of Canada, regulates the energy performance of small residential buildings - 3 storey or less and has less than 600 m² of floor area. For the buildings located in regions with heating degree-days of more than 7000 and equipped with heat recovery ventilation (HRV) systems, the minimum effective thermal resistance needs to be larger than 3.08 m²K/W. For other buildings that are not regulated by the National Building Code, the value is 5.46 m²K/W, as stated in the Energy Code of Canada for Buildings (NRC 2015b), with or without HRV systems.

Exterior wood-frame walls are the most common type of residential wall in Canada and these walls are often used as shear walls in low and mid-rise buildings. To increase the thermal insulation to meet a higher standard of building energy efficiency, exterior wall assembly configurations different from current time-tested practice have been proposed continuously. For example, adding a layer of continuous thermal insulation exterior to the between-stud cavity insulation is getting more popular in practice. This has

the benefit of removing thermal bridging of the lumber members. In the cases that the continuous insulation is put outer to the wood sheathing, the addition of continuous impermeable thermal insulation may result in trapping of moisture and hence significantly reduce the drying capacity of a wall system. The wooden materials used in these walls are vulnerable to biological degradation caused by moisture, which typically occurs first at the wall sheathing in the form of mould, fungal growth or rot. Another modified configuration is to insert a layer of foam insulation between wood-based sheathing and lumber. However, the racking resistance of the shear wall is compromised due to the soft foam layer inserted between lumber and wood-based panels. Clearly there are contradicting influences on thermal and structural performance of the wall when the insulation thickness changes. Exterior walls are often used as shear walls in wood-frame buildings. Moreover, the hygrothermal performance of these new construction approaches has not been fully investigated.

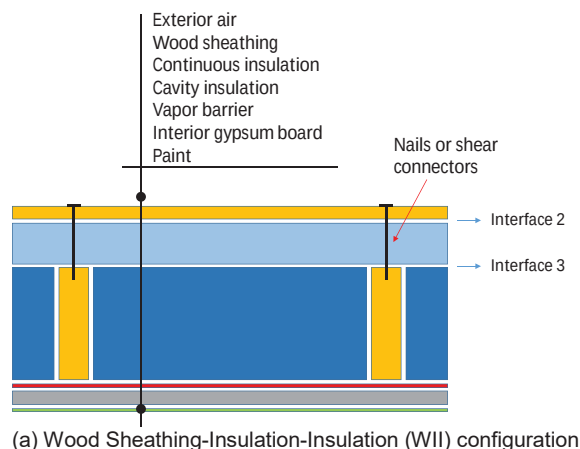
Moisture, from whatever sources, is commonly regarded as the single greatest threat to the durability and long-term performance of the housing stock (Newport Partners Report, 2004). Based on a survey presented by Tsongas (2000) of 334 Iowa households, 98% of the residents reported at least one type of moisture problem. The most common

types of moisture problems were: condensation on windows (62%), exterior paint peeling (41%), staining of interior windows frames and sills (31%), mildew on walls/ceilings or closets (23%), decay/rotting of interior window frames/sills (20%), moisture/mildew problems in summer (18%), frost/condensation on walls/ceilings (13%), and interior paint peeling (10%). A survey of the moisture problems in Canadian residential buildings in the early 1980s has been conducted by Rousseau (1982), categorized by geolocations and moisture problems.

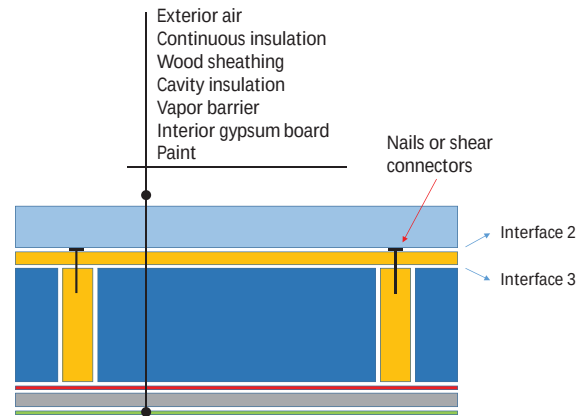
Canada's climate is characterized by its diversity, as temperature and precipitation differ significantly depending on location and time of the year. That is why different assembly configurations have to be proposed for different geolocations. This paper presents some preliminary results from a study aimed at providing design information for selecting wall assemblies with optimized hygrothermal and structural performance to meet building code requirements on energy efficiency and lateral load resistance at different geographical locations.

2. Methodology and Results

Two configurations (Figure 1) were investigated in this study. The main difference between them is the location of the exterior continuous insulation. The wood sheathing in the "Wood sheathing-Insulation-Insulation" (WII) configuration (Figure 1a) is outer to the continuous insulation. The wood sheathing in the "Insulation-Wood sheathing-Insulation" (IWI) configuration (Figure 1b) is sandwiched between the vapor barrier and the continuous insulation with low permeability.



(a) Wood Sheathing-Insulation-Insulation (WII) configuration



(b) Insulation-Wood Sheathing-Insulation (IWI) configuration

Figure 1: Two configurations of wood-frame exterior walls.

2.1 Influence of insulation thickness on shear wall strength

It has been shown that racking strength of a wood-based shear wall is directly proportional to the strength of the sheathing-to-framing nail joint at the perimeter framing of the shear wall panel (Ni et al 2012). Indeed, according to the Canadian timber design standard, CSA O86 (CSA 2014), the shear resistance of a shear wall per unit length of wall, v_r , can be calculated using the simple relationship,

$$V_T = \frac{N_u}{s} \quad (1)$$

where

v_r = shear strength of shear wall, N/mm

N_u = strength of a nail joint, N

s = spacing of nails at perimeter framing members, mm

Plesnik et al (2016) undertook a testing program to evaluate the influence of an intermediate insulation layer between wood-based sheathing and lumber on lateral strength of nail joint that consists of oriented strand board (OSB) as sheathing and spruce-pine-fir no. 2 grade lumber as framing member. Two nail sizes were used: 3.66mm x 76mm and 4.06mm x 89mm. Selected results from their work for 1/4", 1/2", 1" and 1-1/2" insulation thicknesses are presented in Table 1. It can be seen that as expected the strength of nail joint and therefore shear wall decreases as the insulation thickness increases. For the 4.06mm nail, a 1-1/2" insulation will cause a strength reduction of 58 percent. The rate of strength reduction appears more significant when a smaller nail of 3.66mm diameter is used.

The most common nail spacing used in residential shear wall construction is 150mm. Equation above shows that the shear wall strength per unit length can be recovered by using a closer nail spacing. For instance, if an insulation thickness of 1" (25.4mm) is used, for a nail size of 4.06mm diameter a nail spacing of 89mm could be used, which would allow

the shear wall to have the same shear resistance as the same shear wall without the insulation layer but a nail spacing of 150mm.

Table 1 – Percent reduction in nail joint strength due to presence of foam insulation between wood-based sheathing and lumber (Plesnik et al 2016)

	3.66mm x 76mm	4.06mm x 89mm
0	100%	100%
6.4	59%	95%
12.7	53%	85%
25.4	34%	59%
38.1	-	42%

2.2 Hygrothermal performance under 1D steady state vapor diffusion

Table 2 Material properties selected for investigation (steady-state simulation)

Components	Materials	Thickness mm	Conductance W/(K·m ²)	Conductivity W/(K·m)	Permeance ng/(Pa·s·m ²)	Permeability ng/(Pa·s·m)
Exterior	Air	n/a	24	n/a	∞	n/a
Rigid insulation	Extruded polystyrene (with	varies	varies	0.03 or 0.05	varies	1.2 or 2
Sheathing	OSB	12.7	8.3		200	
Cavity insulation	Mineral wool	150	0.27	0.04	1110	
Vapor barrier	Polyethylene	n/a	∞		2 or 4	
Gypsum board	Gypsum wallboard	12.7	12.60	0.16	2200	
Paint	Water-based paint	n/a	∞		150	
Interior	Air	n/a	9	n/a	∞	n/a

Table 3 Parameters investigated for sensitivity analysis

Parameters	Values
Exterior temperature	From -10 to -40 C, in an increment of 2 C
Interior temperature	20 C constant
Exterior relative humidity	90% constant
Interior relative humidity	50% constant
Exterior continuous insulation	
Conductivity	0.03 and 0.05W/(K·m)
Permeability	1.2 and 2 ng/(Pa·s·m)
Thickness	5 to 50 mm, in an increment of 5 mm
Permeance of vapor barrier	2 and 4 ng/(Pa·s·m ²)

Based on the previous investigation on the structural performance, the cavity thickness to be investigated ranges from 0 to 50 mm. To investigate the hygrothermal performance of these two configurations, sensitivity analysis is conducted under steady state heat and moisture transfer situations. The hygrothermal properties of the different layers of the two wall configurations are listed in Table 2. The parameters that are taken for sensitivity analysis are listed in Table 3. For a 25-mm thick exterior continuous insulation with 0.03 W/(K·m) conductivity, the total nominal thermal resistance is 4.89 (K·m²) /W for both the IWI and WII configurations. This value will be 5.73 (K·m²) /W for a thickness of 50 mm. The effective thermal resistance of the wall will be less than the nominal value due to the presence of the wood studs, but it will meet the highest building code requirement using standard 2x6 wood studs at 18" spacing.

Four sets of simulation were conducted. In the first set, 0.03 W/(K·m) and 1.2 ng/(Pa·s·m) for the continuous insulation, and 2 ng/(Pa·s·m²) for vapor barrier were used. Then one of these three parameters was changed in other three sets of simulation. The simulation was used to locate the interface at which condensation would happen under different exterior temperature and insulation thickness.

The heat flow q_T through the non-wood-stud wall section was determined using Eq. (2). Then the temperature at each interface $T_{interface}^i$ was calculated using Eq. (3). Based on the interface temperature, the saturated vapor pressure $P_{saturated}^i$ at the corresponding interface can be determined using published data (ASHRAE 2017).

$$q_T = \frac{T_{int} - T_{ext}}{R_{total}} \quad (2)$$

where

R_{total} is the total thermal resistance of the non-wood-stud section

$$T_{interface}^i = T_{ext} + q_T \sum_{i=1}^n R_i \quad (3)$$

where

R_i is the thermal resistance of the i-th layer

n is the total number of wall layers since the exterior air

Due to water vapor pressure difference between the interior and exterior air, vapor will diffuse through the wall assemblies. Assuming continuous vapor flow, the vapor flow q_v through the non-wood-stud wall section is determined using Eq. (4). Then the vapor pressure P_{CF}^i under the continuous vapor flow assumption at each interface was calculated using Eq. (5). If at one interface, $P_{saturated}^i$ is less than P_{CF}^i , condensation will occur at this interface. This comparison starts from the most inner interface to exterior.

$$q_v = (P_{int} - P_{ext})m_{total} \quad (4)$$

where

m_{total} is the total water vapor permeability of the non-wood-stud section

$$P_{CF}^i = P_{ext} + \frac{q_v}{\sum_{i=1}^n m_i} \quad (5)$$

where

m_i is the permeability of the i-th layer

n is the total number of wall layers since the exterior air

The results are presented in Figure 2. The colored cells in the tables show the conditions at which interface condensation will occur. Number 0 means no condensation takes place within wall assemblies. In WII configuration, interface 2 is between OSB sheathing and exterior continuous insulation, interface 3 is between exterior continuous and cavity insulation. In IWI configuration, interface 2 is between exterior continuous and OSB sheathing, interface 3 is between OSB sheathing and cavity insulation.

0.03 conductivity		Exterior insulation thickness (mm)											0.03 conductivity		Exterior insulation thickness (mm)										
2 vapor barrier		5	10	15	20	25	30	35	40	45	50		2 vapor barrier		5	10	15	20	25	30	35	40	45	50	
1.2 permeability	-10	0	0	0	0	0	0	0	0	0	0		1.2 permeabi	-10	0	0	0	0	0	0	0	0	0	0	
	-12	0	0	0	0	0	0	0	0	0	0			-12	0	0	0	0	0	0	0	0	0	0	
WII	-14	0	0	0	0	0	0	0	0	0	0		IWI	-14	0	0	0	0	0	0	0	0	0	0	
	-16	0	0	0	0	0	0	0	0	0	0			-16	0	0	0	0	0	0	0	0	0	0	
Exterior temperature (c)	-18	0	0	0	0	0	0	0	0	0	0			-18	0	0	0	0	0	0	0	0	0	0	
	-20	0	0	0	0	0	0	0	0	0	0			-20	0	0	0	0	0	0	0	0	0	0	
	-22	0	0	0	0	0	0	0	0	0	0			-22	0	0	0	0	0	0	0	0	0	0	
	-24	0	0	0	0	0	0	0	0	0	0		Exterior temperature	-24	0	0	0	0	0	0	0	0	0	0	
	-26	0	0	0	0	0	0	0	0	0	0			-26	0	0	0	0	0	0	0	0	0	0	
	-28	0	0	0	0	0	0	0	0	0	0	0			-28	0	0	0	0	0	0	0	0	0	0
	-30	0	0	0	0	0	0	0	2	2	2	2			-30	0	0	0	0	0	0	0	0	0	0
	-32	3	3	2	2	2	2	2	2	2	2			-32	3	3	0	0	0	0	0	0	0	0	
	-34	3	3	3	3	3	2	2	2	2	2			-34	3	3	3	3	3	0	0	0	0	0	
	-36	3	3	3	3	3	3	3	2	2	2			-36	3	3	3	3	3	3	3	2	0	0	
	-38	3	3	3	3	3	3	3	3	3	3			-38	3	3	3	3	3	3	3	3	3	3	
	-40	3	3	3	3	3	3	3	3	3	3			-40	3	3	3	3	3	3	3	3	3	3	

(a) 0.03 W/(K·m) and 1.2 ng/(Pa·s·m) for continuous insulation, and 2 ng/(Pa·s·m²) for vapor barrier

0.05 conductivity		Exterior insulation thickness (mm)										0.05 conductivity		Exterior insulation thickness (mm)									
		5	10	15	20	25	30	35	40	45	50			5	10	15	20	25	30	35	40	45	50
	-10	0	0	0	0	0	0	0	0	0	0		-10	0	0	0	0	0	0	0	0	0	0
	-12	0	0	0	0	0	0	0	0	0	0		-12	0	0	0	0	0	0	0	0	0	0
WII	-14	0	0	0	0	0	0	0	0	0	0	IWI	-14	0	0	0	0	0	0	0	0	0	0
	-16	0	0	0	0	0	0	0	0	0	0		-16	0	0	0	0	0	0	0	0	0	0
	-18	0	0	0	0	0	0	0	0	0	0		-18	0	0	0	0	0	0	0	0	0	0
	-20	0	0	0	0	0	0	0	0	0	0		-20	0	0	0	0	0	0	0	0	0	0
	-22	0	0	0	0	0	0	0	0	0	0		-22	0	0	0	0	0	0	0	0	0	0
	-24	0	0	0	0	0	0	0	0	0	0		-24	0	0	0	0	0	0	0	0	0	0
	-26	0	0	0	0	0	0	0	0	0	0		-26	0	0	0	0	0	0	0	0	0	0
	-28	0	3	3	3	3	3	3	3	3	0		-28	0	3	3	3	3	3	3	3	3	2
	-30	3	3	3	3	3	3	3	3	3	3		-30	3	3	3	3	3	3	3	3	3	3
	-32	3	3	3	3	3	3	3	3	3	3		-32	3	3	3	3	3	3	3	3	3	3
	-34	3	3	3	3	3	3	3	3	3	3		-34	3	3	3	3	3	3	3	3	3	3
	-36	3	3	3	3	3	3	3	3	3	3		-36	3	3	3	3	3	3	3	3	3	3
	-38	3	3	3	3	3	3	3	3	3	3		-38	3	3	3	3	3	3	3	3	3	3
	-40	3	3	3	3	3	3	3	3	3	3		-40	3	3	3	3	3	3	3	3	3	3

(b) 0.05 W/(K·m) and 1.2 ng/(Pa·s·m) for continuous insulation, and 2 ng/(Pa·s·m²) for vapor barrier

4 vapor barrier	Exterior insulation thickness (mm)											4 vapor barrier	Exterior insulation thickness (mm)									
	5	10	15	20	25	30	35	40	45	50			5	10	15	20	25	30	35	40	45	50
	-10	0	0	0	0	0	0	0	0	0			-10	0	0	0	0	0	0	0	0	0
	-12	0	0	0	0	0	0	0	0	0			-12	0	0	0	0	0	0	0	0	0
WII	-14	0	0	0	0	0	0	0	0	0		IWI	-14	0	0	0	0	0	0	0	0	0
	-16	0	0	0	0	0	0	0	0	0			-16	0	0	0	0	0	0	0	0	0
	-18	0	0	0	0	0	0	0	0	0			-18	0	0	0	0	0	0	0	0	0
	-20	0	0	0	0	0	0	0	0	0			-20	0	0	0	0	0	0	0	0	0
	-22	0	0	0	0	0	0	0	0	0			-22	0	0	0	0	0	0	0	0	0
	-24	3	3	3	3	2	2	2	2	2			-24	3	3	3	3	0	0	0	0	0
	-26	3	3	3	3	3	3	3	3	2			-26	3	3	3	3	3	3	3	0	0
	-28	3	3	3	3	3	3	3	3	3			-28	3	3	3	3	3	3	3	3	3
	-30	3	3	3	3	3	3	3	3	3			-30	3	3	3	3	3	3	3	3	3
	-32	3	3	3	3	3	3	3	3	3			-32	3	3	3	3	3	3	3	3	3
	-34	3	3	3	3	3	3	3	3	3			-34	3	3	3	3	3	3	3	3	3
	-36	3	3	3	3	3	3	3	3	3			-36	3	3	3	3	3	3	3	3	3
	-38	3	3	3	3	3	3	3	3	3			-38	3	3	3	3	3	3	3	3	3
	-40	3	3	3	3	3	3	3	3	3			-40	3	3	3	3	3	3	3	3	3

(c) 0.03 W/(K·m) and 1.2 ng/(Pa·s·m) for continuous insulation, and 4 ng/(Pa·s·m²) for vapor barrier

2 permeability	Exterior insulation thickness (mm)											2 permeability	Exterior insulation thickness (mm)									
	5	10	15	20	25	30	35	40	45	50			5	10	15	20	25	30	35	40	45	50
	-10	0	0	0	0	0	0	0	0	0			-10	0	0	0	0	0	0	0	0	0
	-12	0	0	0	0	0	0	0	0	0			-12	0	0	0	0	0	0	0	0	0
WII	-14	0	0	0	0	0	0	0	0	0		IWI	-14	0	0	0	0	0	0	0	0	0
	-16	0	0	0	0	0	0	0	0	0			-16	0	0	0	0	0	0	0	0	0
	-18	0	0	0	0	0	0	0	0	0			-18	0	0	0	0	0	0	0	0	0
	-20	0	0	0	0	0	0	0	0	0			-20	0	0	0	0	0	0	0	0	0
	-22	0	0	0	0	0	0	0	0	0			-22	0	0	0	0	0	0	0	0	0
	-24	0	0	0	0	0	0	0	0	0			-24	0	0	0	0	0	0	0	0	0
	-26	0	0	0	0	0	0	0	0	0			-26	0	0	0	0	0	0	0	0	0
	-28	0	0	0	0	0	0	0	0	0			-28	0	0	0	0	0	0	0	0	0
	-30	0	0	0	0	0	2	2	2	2			-30	0	0	0	0	0	0	0	0	0
	-32	2	2	2	2	2	2	2	2	2			-32	0	0	0	0	0	0	0	0	0
	-34	3	2	2	2	2	2	2	2	2			-34	3	0	0	0	0	0	0	0	0
	-36	3	3	2	2	2	2	2	2	2			-36	3	3	0	0	0	0	0	0	0
	-38	3	3	3	2	2	2	2	2	2			-38	3	3	3	0	0	0	0	0	0
	-40	3	3	3	3	3	2	2	2	2			-40	3	3	3	3	3	0	0	0	0

(d) 0.03 W/(K·m) and 2 ng/(Pa·s·m) for continuous insulation, and 2 ng/(Pa·s·m²) for vapor barrier

Figure 2: Results of sensitivity analysis

The following observations can be seen from the simulation results:

- In general, the wall configurations with the chosen material properties will perform well in southern Canada under the chosen interior conditions as condensation occurs only at extremely low outdoor temperatures (less than -30°C). The WII configuration is slightly more vulnerable to within-layer condensation than the IWI configuration.
- For given exterior temperature, the higher the exterior and/or interior relative humidity (RH), the higher the change of within-layer condensation.
- Increasing the conductivity of the continuous insulation and/or the permeability of the vapor barrier will result in condensation at higher exterior temperatures, while increasing the permeability of the continuous insulation will lower the threshold condensation temperature. Low permeability vapor

barrier may represent leaks in vapor barrier, such as nail holes or tape failure.

3. Conclusions and outlook

This study investigates and compares the hygrothermal and structural performance of two proposed wood-frame exterior wall configurations. The impact of the cavity thickness on shear resistance was investigated. Numerical simulations have been carried out to investigate the hygrothermal performance of the walls configurations under steady-state vapor diffusion. Preliminary results have shown that these two wall configurations have similar hygrothermal performance. Materials with high permeability should be used for the continuous insulation. Interior relative humidity higher than 50% would be of interest to consider in further analysis. As for structural performance, the shear wall strength can be predicted by the nailed joint strengths. The use of

insulation between stud and sheathing will reduce the lateral load resistance of the wood-frame shear wall design because the resistance depends on the sheathing-to-lumber nail joint in structural design. However, denser space of nail joints can be used to compensate for the reduction.

Acknowledgements

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Utilizing the Knudsen Effect in the Quest for Super Insulation Materials

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Abstract:

Initiatives to incorporate energy efficiency measures and strategies in the building sector have gained attention for several decades, and with increased focus on zero energy and zero emission buildings, such initiatives will probably still continue to emerge for several more decades to come. Development of new high-performance thermal insulation materials and super insulation materials (SIM) for the advanced building envelopes of tomorrow may play an essential role in this regard. Very thick building envelopes are not desirable due to several reasons, e.g. considering space issues with respect to both economy, floor area, transport volumes, architectural restrictions and other limitations, material usage and existing building techniques. Hence, the stage is set for the development of new thermal insulation materials with a very low thermal conductivity, thus allowing the usage of relatively thin building envelopes with a very high thermal resistance and thereby substantially reduced heat loss. In porous materials, when the mean free path of the gas molecules becomes larger than the pore diameter, there will be a decrease in the gas thermal conductivity including the gas and pore wall interaction, which is referred to as the Knudsen effect. This study will present our on-going efforts utilizing the Knudsen effect attempting to make SIMs with a nanoporous air-filled structure at atmospheric pressure, i.e. nano insulation materials (NIM). Some possible pathways to NIMs and SIMs like e.g. the template foaming method and the internal gas release method are promising with respect to their high potential, however, so far large experimental challenges have made us abandon these methods for the moment. That is, currently we are pursuing to make NIMs by the sacrificial template method, more specifically by the synthesis of hollow silica nanospheres (HSNS), where both the inner sphere diameter and shell thickness may be tailor-made and thereby determining the thermal conductivity.

Keywords:

Knudsen effect, super insulation material, nano insulation material, hollow silica nanosphere, thermal conductivity.

1. Introduction

The society of today is demanding an ever increasing focus on energy producing and energy saving strategies in several fields, where one of these is the building sector. In that respect, the development of high-performance thermal insulation materials may play a crucial role, where these are often denoted as super insulation materials (SIM). It has also been pointed out that energy efficiency measures are the most cost-effective ones, whereas measures like e.g. solar photovoltaics and wind energy are far less cost-effective than thermal insulation retrofitting of buildings regarding the global greenhouse gas (GHG) abatement costs [1]. Hence, there is a growing drive to develop SIMs for building applications also incorporating environmental aspects. The objective of the study presented herein is to investigate the opportunities for utilizing the Knudsen effect in the quest for developing SIMs. That is, nanoporous materials with low thermal conductivity values are being attempted made, i.e. nano insulation materials (NIM), where one of the possible pathways is through the development of hollow silica nanospheres (HSNS) by a sacrificial template method. Variations and optimizations of synthesis parameters are pursued in order to tailor-make HSNS with specific inner sphere

diameters and shell thicknesses, with a final aim to reach as low thermal conductivities as possible.

2. The Knudsen effect

In short, the Knudsen effect may be described as an effect which occurs when the thermal conductivity is decreased in nanoporous materials due to the mean free path of the gas molecules becoming larger than the pore diameter, i.e. pore diameters typically in the nanorange.

Taking into account the Knudsen effect, the thermal conductivity $\lambda_{\text{gas,gas-solid}}$, which in addition to the gas conductivity also includes the gas and pore wall interaction, may be written in a simplified way as [2-7]:

$$\lambda_{\text{gas,gas-solid}} = \frac{\lambda_{\text{gas},0}}{1 + 2\beta\text{Kn}} = \frac{\lambda_{\text{gas},0}}{1 + \frac{\sqrt{2}\beta k_B T}{\pi d^2 p \delta}} \quad (1)$$

where

$$\text{Kn} = \frac{\sigma_{\text{mean}}}{\delta} = \frac{k_B T}{\sqrt{2}\pi d^2 p \delta} \quad (2)$$

where $\lambda_{\text{gas,gas-solid}}$ = thermal conductivity including the gas thermal conductivity and the gas and pore wall

interaction ($W/(mK)$), $\lambda_{\text{gas},0}$ = gas thermal conductivity in the pores at STP (standard temperature and pressure) ($W/(mK)$), β = coefficient characterizing the molecule-wall collision energy transfer (in)efficiency (between 1.5 - 2.0), k_B = Boltzmann's constant $\approx 1.38 \cdot 10^{-23}$ J/K, T = temperature (K), d = gas molecule collision diameter (m), p = gas pressure in pores (Pa), δ = characteristic pore diameter (m), and σ_{mean} = mean free path of gas molecules (m).

When attempting to develop SIMs the thermal transport by solid state conductance and radiation must also be minimized. Noteworthy, in a nanoporous material, the thermal transport by convection will normally be negligible.

3. Experimental

There may be several pathways to develop SIMs through NIMs, including membrane foaming and gas release methods [8-9], probably also hitherto unknown methods, but currently we are investigating the sacrificial template method by making hollow silica nanospheres (HSNS) [8-9].

In short, spherical templates are first made, e.g. polystyrene (PS) spheres, which thereafter are coated with a silica layer using e.g. tetraethyl orthosilicate (TEOS) or water glass (Na_2SiO_3) as the silica precursor. Finally, the sacrificial PS templates are removed by a heating process where the PS template material is evaporated and diffused through the silica shell, thus leaving the final result as silica shells around spherical voids, i.e. HSNS. An illustration of the HSNS synthesis is depicted in Fig.1.

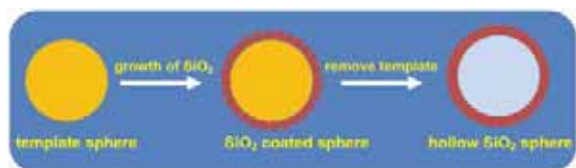


Fig.1. HSNS synthesis illustrated.

4. Results and discussion

The various parameters for the HSNS synthesis have been investigated, although far from fully, and have resulted in different HSNS formations where some have been more successful than others. For further information on the miscellaneous HSNS syntheses and their resulting properties it is referred to our earlier studies [10-14] and forthcoming ones.

Two key parameters are to control the sphere inner diameter and the sphere shell thickness. The sphere inner diameter is a key parameter in the Knudsen equation as given in Eq.1, thus part of determining the thermal conductivity including the gas thermal conductivity and the gas and pore wall interaction. That is, in principle, the smaller the inner sphere pore diameter the lower thermal conductivity (when not

taking into account other varying parameters). The sphere shell thickness will also influence the thermal conductivity, i.e. in this case more specifically the solid state conductivity, and also the mechanical strength properties.

The sphere composition and surface roughness will also have an effect on the thermal conductivity and mechanical strength properties. The produced HSNS may have shells composed of silica nanoparticles with different diameters depending on the actual synthesis method and parameters. The surface roughness of the HSNS may also vary greatly with the chosen synthesis, i.e. a rough surface from a shell made of silica nanoparticles (TEOS as silica precursor) or a large, wrinkled silica sheet (water glass as silica precursor), the latter surface appearing much smoother than the former one [15].

Yet another key parameter is the packing of the HSNS, which will directly influence the voids formed between the HSNS and the solid state connections between the HSNS, i.e. the former one having an impact on the thermal conductivity including the gas thermal conductivity and the gas and pore wall interaction and the latter one having an effect on the solid state conductivity. These aspects are influenced by the size of the HSNS, i.e. the inner pore diameter and the shell thickness, and the outer morphology of the HSNS, i.e. the exterior surface roughness.

Typically, so far the thermal conductivity of the HSNS powder samples has varied between 20 to 90 mW/(mK), though there are some uncertainties with the Hot Disk apparatus method which have to be further clarified. However, there is an expressed goal to lower the thermal conductivity below 20 mW/(mK).

The sacrificial template synthesis is a crucial step in the making of HSNS. It is a rather hard challenge to make monodisperse PS template spheres with diameters below 100 nm. In Fig.2 there are given scanning electron microscope (SEM) images of PS spheres with diameters 80 nm and 195 nm, where the former ones represent a hard-gained effort in itself.

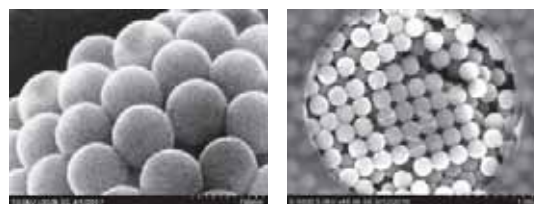


Fig.2. PS sphere SEM images with diameters 80 nm (left) and 195 nm (right). Magnification 350 000x (left) and 45 000x (right), scale-bar 100 nm (left) and 1 μm (right).

Examples of HSNS with two different inner diameters are depicted in the SEM images given in Fig.3 and Fig.4. These examples display rather rough HSNS surfaces due to the relatively large silica nanoparticles

(compared to the HSNS diameters) which the HSNS shells are composed of. Hence, modification and optimization of the HSNS shells may enable us to tailor-make NIMs and SIMs with the desired thermal and mechanical properties. These aspects will be investigated in forthcoming studies within the project High-Performance Nano Insulation Materials [16].

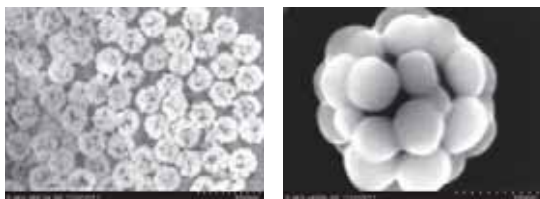


Fig.3. SEM images of HSNS with inner diameters 85 nm, several spheres (left) and a single sphere (right). Magnification 60 000x (left) and 400 000x (right), scale-bar 500 nm (left) and 100 nm (right).

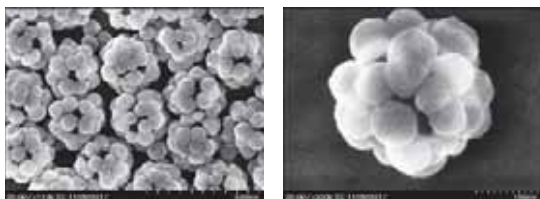


Fig.4. SEM images of HSNS with inner diameters 135 nm, several spheres (left) and a single sphere (right). Magnification 110 000x (left) and 300 000x (right), scale-bar 500 nm (left) and 100 nm (right).

5. Conclusions and outlook

In the quest for super insulation materials (SIM), nano insulation materials (NIM) have been made by various syntheses of hollow silica nanospheres (HSNS), where the resulting HSNS and their properties are very dependent on several parameters during the syntheses. Optimization and fine-tuning of these synthesis parameters will be important in the forthcoming experimental investigations.

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Condition Assessment of Bridges using Non-Contact Vibration Measurement: A Pilot Study

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Abstract:

Damage detection using measurement of change in the vibration signature of bridges is a well known fundamental technique which requires acquisition of vibration data of the bridge from mounted sensors such as accelerometers. Mounting multiple accelerometers and building a wireless network to monitor the vibration response can sometime become troublesome and very expensive to maintain. Also, the mounted accelerometers are very difficult to synchronize with each other to obtain the modal parameters of the bridge. This paper illustrates the use of a Laser Scanning Vibrometer (LSV) as a non contact damage detection technique for bridges. The LSV available at University of Victoria's Facility for Innovative Materials and Infrastructure Monitoring (FIMIM) can obtain the vibration response of a bridge from 100'. The LSV was used to compare the data obtained by the mounted sensors on the Portage Creek Bridge, Victoria, British Columbia, Canada during ambient vibration condition. Multiple points on the East Span of the bridge were selected to compare the data. The paper also described the various challenges faced by the authors during the measurement.

Keywords:

Non-Contact Vibration Measurement, Laser Scanning Vibrometer, Structural Health Monitoring, Bridges, and Non-Destructive Evaluation

1. Introduction

Study of the vibration signature of a structure periodically and estimating the performance of the structure is not a new concept. This is a very fundamental concept which is being used for detecting damage for a number of years [1-4]. The presence of damage or deterioration in a structure causes changes in the mass and or stiffness and hence changes in natural frequencies of the structure. Monitoring the natural frequency over the period and studying the changes can give information about the behavior of the structure. The most useful damage location methods (based on dynamic testing) are probably those using changes in resonant frequencies because frequency measurements can be quickly conducted and are often reliable [5]. Abnormal loss of stiffness is identified when measured natural frequencies are significantly lower than expected. A study led by Morgan et al. stated that frequencies higher than expected are indicative of supports stiffer than expected [6]. It would be necessary for a natural frequency to change by about 5% for damage to be detected with confidence [7]. However, it has been found that the significant frequency changes alone do not automatically imply the existence of damage since frequency shifts (exceeding 5%) due to changes in ambient conditions have been measured [8] for both concrete and steel bridges within a single day. It was found that the long-term changes of natural

frequencies correlate well with the long-term changes of temperature [9].

Results from some experimental and numerical studies have suggested that the lower vibration modes would probably be best suited for damage detection [10]. However, Begg et al. [11] stated that modes higher than the first should be used in damage detection to improve the identification. The increased sensitivity of the higher modes to local damage has also been mentioned by others [12, 13].

For an effective utilization of dynamic testing as a diagnostic tool, it is necessary to understand the effects of deterioration and defects on the dynamic characteristics of structural systems. For example, long span bridges are not likely to show measurable changes in dynamic properties if local damage is sustained [14]. In addition, dynamic characteristics are sensitive to changes in support conditions that may have little structural consequence. Responses measured at boundaries (abutment, piers and other support types) could also yield erroneous results [15]. It is also important that the effects of environmental factors, such as temperature and humidity, on changes in dynamic characteristics be either small or predictable [16]. Identification of a 'sufficient' number of frequency variations may be necessary before defects can be adequately located. For safety inspection of long span suspension bridges, detection of natural frequency changes in the order of 0.01 Hz may be required [17].

Commercially available high resolution wired accelerometer system when compared with the Laser Vibrometer [18] shows that using LSV at frequency below 1 Hz, an uncertainty component due to threshold and resolution better of at least 1000 times can be obtained. This is due to the fact that the lowest displacements can be measured at higher frequencies, for example at 1 Hz, using the best transducers available, the measured displacement drops to about $2.5 \mu\text{m}$ [18]. It should be noted that the proposed research uses the PSV 500 from Polytec having better specifications compared to the one from Polytec OFV-303 used in the literature [18].

LSV uses the Laser Doppler Technique to measure the velocity of the object directly. Due to the Doppler effect, the light back-scattered from the moving target carries information about the motion quantities velocity and displacement at the point of incidence: Displacement of the surface modulates the phase of the light wave while instantaneous velocity shifts its optical frequency by a small amount. Because the optical frequency of the laser is far too high to demodulate directly (5×10^{14} Hz), interferometric techniques are employed to reveal the measurement effects. With the help of an interferometer the received light wave is mixed with a reference beam so that the two heterodyne on to the surface of a photodetector [19].

Another research [20] on the comparison of contact sensors with non-contact laser vibrometer shows that the use of the laser Doppler vibrometer (LDV) system as a non-contact, non-destructive means of measuring bridge vibration and deflection can provide accurate results. It has also been reported that the LDV can be used to map the bridge response at various locations while the contact sensors only offer information about a particular location [20].

Laser Vibrometer was employed to develop a structural damage model by Siringoringo et al. [21]. In this study [21], authors used modal updating technique. The essential feature of this method was the non-iterative solving technique of inverse problem, which allows damage to be located and quantified by employing the modal parameters obtained before and after damage. Numerical simulation and laboratory-scaled experiments using bolted lap joint plate demonstrated that this technique can detect locations and magnitude of damage with incomplete modal information [21].

2. Experimental Work

Lab Experiment:

Before conducting an experiment at the Portage Creek Bridge, authors performed a small experiment in the Facility for Innovative Materials and Infrastructure Monitoring (FIMIM) to sense the displacement values obtained using LSV. For this, LSV was used to obtain displacement histories of a 12" long aluminum ruler as seen in Figure 1.

The vertical displacement of the ruler was measured using a highly sensitive displacement gauge and compared with LSV. Two different sampling rates 2.5 kHz (High) and 250 Hz (Low) were selected to see the performance. Displacement histories at both the sampling frequencies are presented here in Figures 2 and 3. It should be noted that the LSV system (PSV-500) available at FIMIM measures the velocity directly and since it is a digital system without any analog signal, the software performs the integration and display to displacement with less than 1% error on the measurement.



Fig. 1: Test Setup- Side View

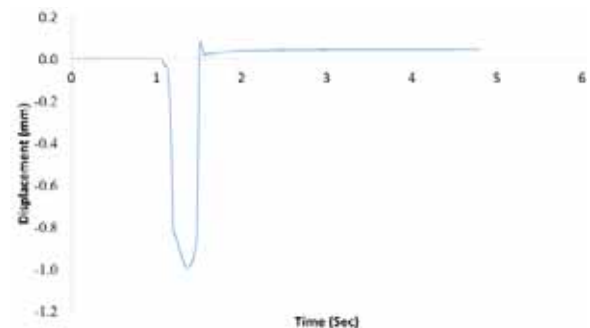


Fig. 2: Displacement using LSV at 2.5 kHz Sampling rate

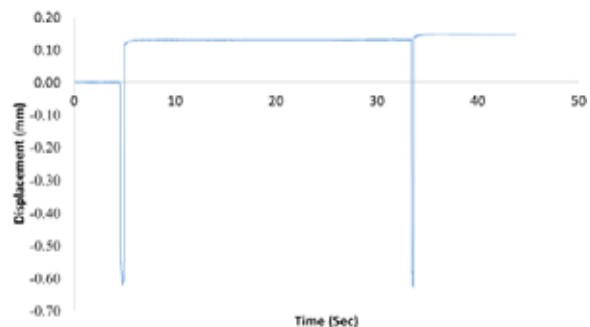


Fig. 3: Displacement using LSV at 250 Hz Sampling rate

Table 1 shows the maximum displacement values recorded using both LSV and a displacement gauge. It can be seen that the values obtained using LSV is

very close to the value obtained using a displacement gauge.

Table 1: Vertical displacement values obtained using LSV and a displacement gauge

Test #	Stroke	Instrument/Sensor	Max Displacement
1 (2.5 kHz)	1	LSV	1 mm
		Deflection Gauge	Gauge reading-37 → 0.925 mm
2 (250 Hz)	1	LSV	625 μm → 0.625 mm
		Deflection Gauge	Gauge Reading-21 → 0.525 mm
	2	LSV	725 μm → 0.725 mm
		Deflection Gauge	Gauge Reading-27 → 0.675 mm

It should be noted that this experiment was conducted just to have a sense of the displacement values obtained using the LSV and hence for this, a highly sophisticated experimental setup was not required.

Field work:

Portage Creek Bridge was constructed in 1983 with three spans over the interurban road, Victoria BC, Canada. It is a concrete-steel composite structure with concrete deck and steel girders. Detailed information on the superstructure is given in [22]. This particular bridge has caught a lot of attention as the bridge was designed long before the introduction of current seismic design standards. The bridge has also undergone a seismic retrofit in 2003 by SIMTREC (Structural Innovation and Monitoring Technologies Resource Centre (Formerly known as ISIS Canada). This bridge is currently being monitored by BC Ministry of Transportation and Infrastructure (BC MOTI) as a part of the BCSIMS (Strong Motion Network and Seismic Structural Health Monitoring Network of British Columbia) project.

As a part of the seismic assessment, Portage Creek Bridge was selected for a dynamic analysis using modal updating technique in 2014. The study was carried out by Yu Feng et al. [22] and during the study they have found out the dynamic characteristics like modal frequency, damping ratio and mode shape using multiple mounted accelerometers and modal updating technique. As a first exercise, authors of this paper have tried using non-contact LSV to obtain the vibration response of the structure and compare it with the mounted accelerometer data.

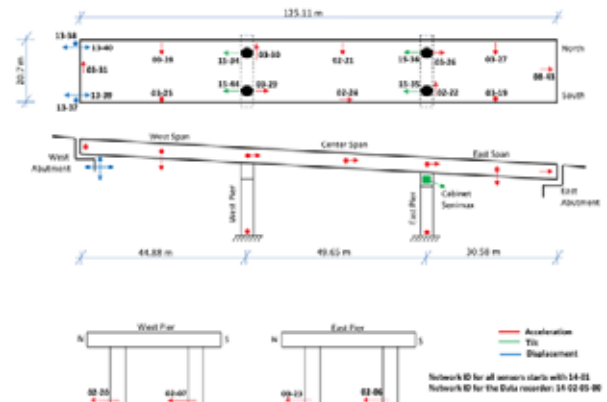


Fig. 4: Sensor Map of Portage Creek Bridge, Victoria BC

The bridge structure is equipped with a total of 20 sensors out of which 4 are for tilt measurement, 2 are for displacement, and the rest 14 are for acceleration measurement. Figure 4 shows the location of different sensors with their network ids.



Fig. 5: Experimental Setup: Portage Creek Bridge Site

For this pilot study, out of the three spans, only one span (east span) was selected as it was easily accessible. Figure 5 shows the measurement location at the Portage Creek Bridge Site. All three girders of the east span were chosen for the measurement. For simplicity, one point (mid point) on each girder was selected as seen in Figure 6. Figure 6 also shows the traffic direction (Shown with the arrows) on the McKenzie Ave. It should be noted that only 2-axle trucks were considered as an ambient traffic in this study.

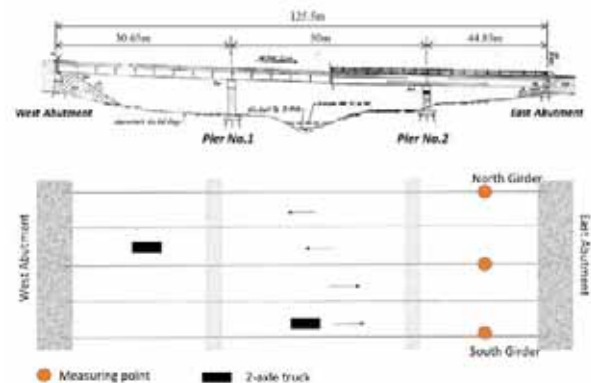


Fig. 6: Vibration Monitoring during Ambient Traffic

Following Table 2 shows the different traffic events that were considered.

Table 2 Different Traffic Events

Girder	Event	Measurement
South Girder	No traffic event	Acceleration and Displacement
	Truck above event	Acceleration and Displacement
North Girder	Truck away event	Acceleration and Displacement
Middle Girder	Truck away event	Displacement

Figures 7 and 8 below show the graphical representation of the “truck above” event and “truck away” event.

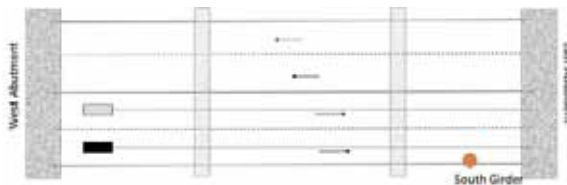


Fig. 7: Truck above Event - South Girder

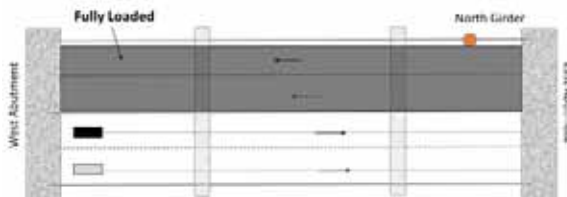


Fig. 8: Truck away Event - North Girder

It should be noted that the truck above event for north girder was not captured due to the heavy traffic on that lane. In Figure 8, fully loaded shows the high volume of static traffic on that particular lane.

3. Results and Discussion

To obtain the vibration response of the structure and compare the data with the mounted sensors, the LSV was set up right under the girder. This study was carried out on 2nd August 2017. The challenge was to shoot the laser beam perpendicular to the vibrating surface. As shown in Figure 9, the laser beam was focused next to the mounted accelerometer for both North and South girders.

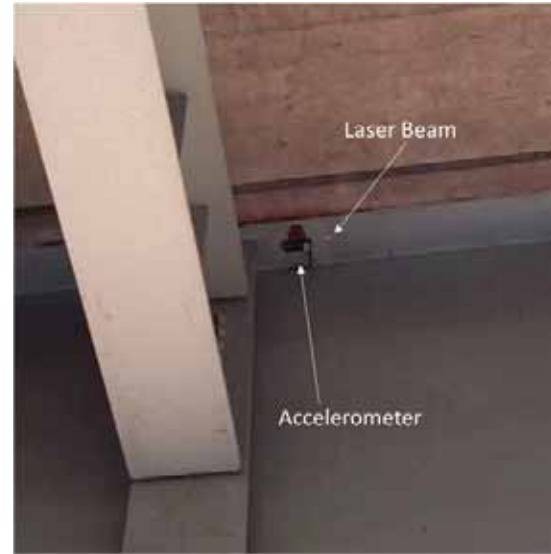


Fig. 9: Laser beam location

The sampling frequency of the LSV used was 250 Hz and maximum acquisition time was 225 seconds for every event of displacement and acceleration measurement.

South Girder:

As can be seen in Figures 10 and 11, the maximum magnitude of the acceleration without traffic and with a truck passing above were 0.14 and 4.1 m/s² respectively for the south girder.

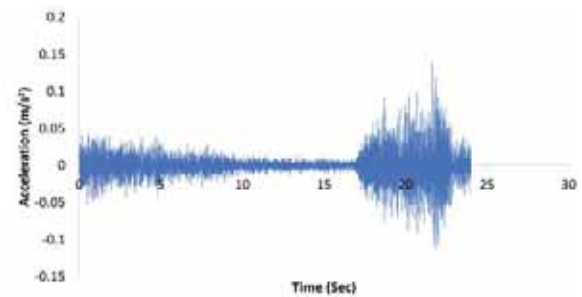


Fig. 10: Acceleration history of South Girder - No traffic event

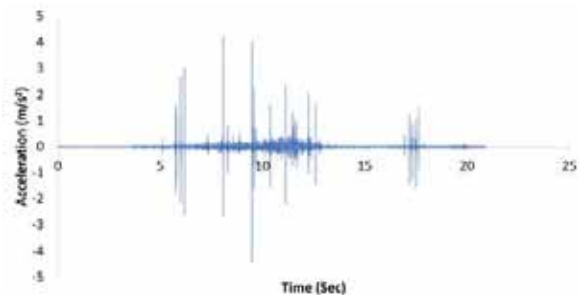


Fig. 11: Acceleration history of South Girder- Truck above event

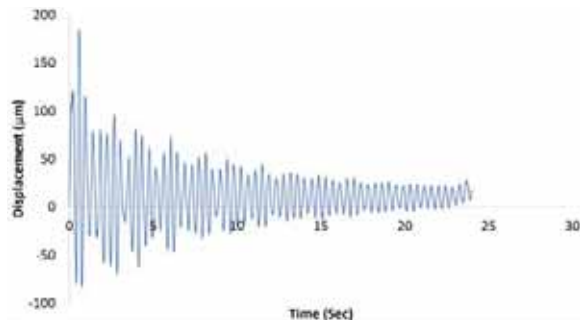


Fig. 12: Displacement history of South Girder- No traffic event

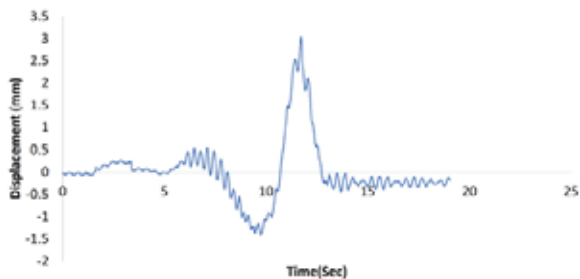


Fig. 13: Displacement history of South Girder- Truck Above event

The total maximum vertical displacement values during no traffic event and the truck above event were found to be 275 μm and 4.5 mm respectively (Figures 12 and 13). In addition to this, the displacement history captured shows the harmonic response of the structure.

Middle Girder:

It should be noted that there was no mounted accelerometer on the middle girder. Only displacement history was recorded using the LSV as shown in Figure 14. Due to high volume of static traffic on the lane above at the time of testing, only the truck away event was captured. The maximum total vertical displacement was found to be 1 mm.

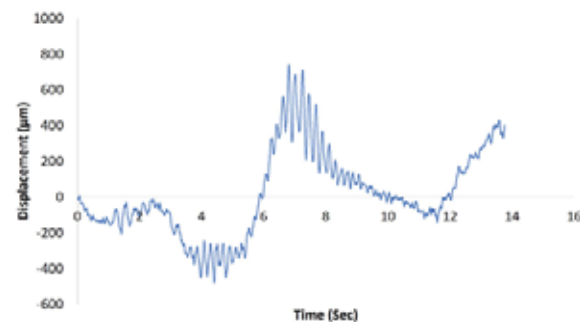


Fig. 14: Displacement history of Middle Girder- Truck away event

North Girder:

Figures 15 and 16 show acceleration and displacement histories of north girder during the "Truck away" event respectively. "No traffic" event was not captured at that time due to heavy traffic on that particular lane. It could be seen that the maximum acceleration was found to be 2.8 m/s^2 & -3 m/s^2 and displacement was found to be -100 μm & 200 μm .

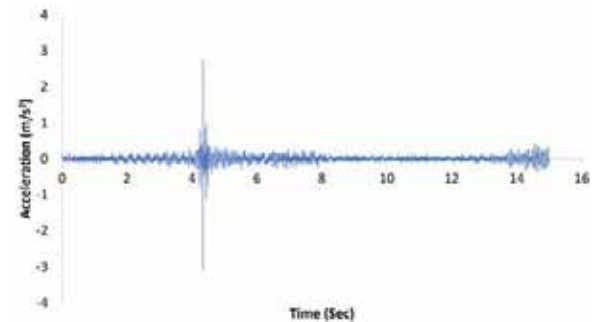


Fig. 15: Acceleration history of North Girder- Truck away event

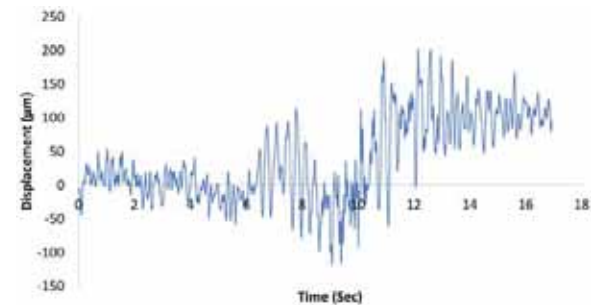


Fig. 16: Displacement history of North Girder- Truck away event

Mounted Sensors:

The time interval set between two measurements of the mounted sensors was 6 min for each sensor at certain threshold value to efficiently use the battery power. The authors found that the threshold values set by the sensor manufacturers were too high for the accelerometers and hence no data were recorded during the time LSV readings were gathered.

Following Figures 17-20 show the tilt measurements of both the cap beams. Direct comparison of the tilt measurements and the LSV data can not be made as the LSV data is in the form of either vertical acceleration or vertical displacements.

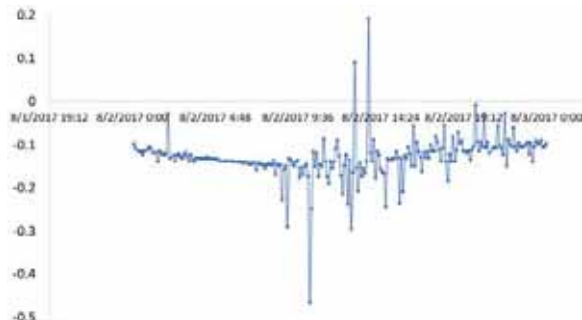


Fig. 17: Tilt (measured in degree) history - Sensor ID-15-44

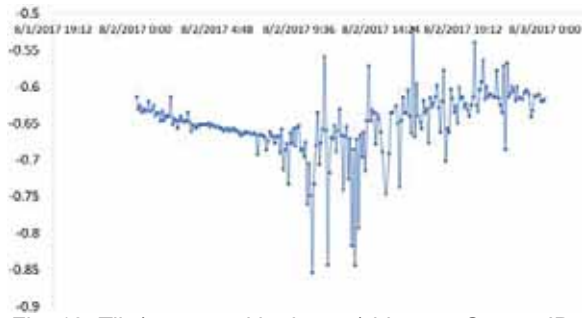


Fig. 18: Tilt (measured in degree) history - Sensor ID-15-34

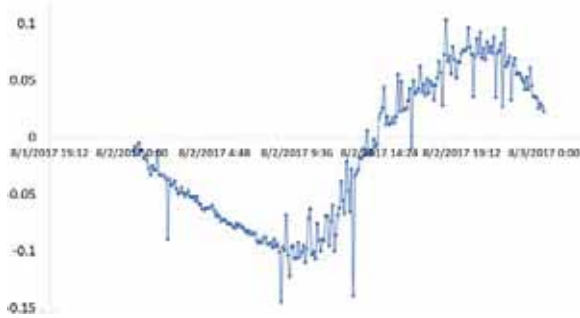


Fig. 19: Tilt (measured in degree) history - Sensor ID-15-35

Maximum tilts were recorded to be -0.45, -0.85, -0.14 and +0.91 degree for sensor 44, 34, 35 and 36 respectively. Negative sign presents the opposite direction of tilt.

Displacement sensor mounted on the abutment recorded the total displacement of 11 mm (Figure 21) in horizontal direction over the entire day.

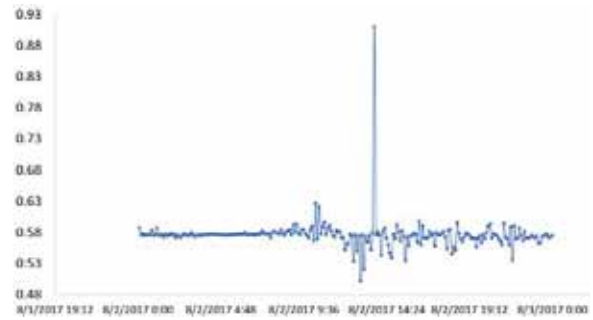


Fig. 20: Tilt (measured in degree) history - Sensor ID-15-36

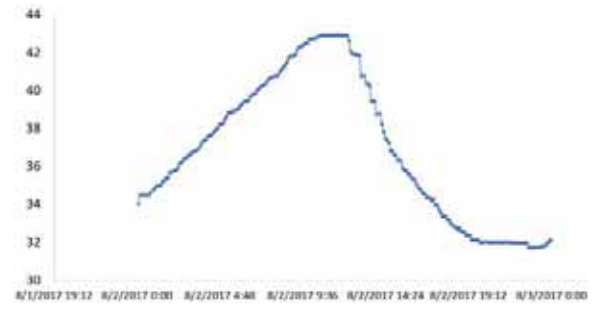


Fig. 21: Displacement (measured in mm) history - Sensor ID-13-39

4. Conclusions and outlook

The paper demonstrates the use of LSV out on the field to measure the vibration response of the structure by means of true displacement values during the ambient traffic. The data recorded using LSV were very accurate and matched with the response of the structure. Unfortunately, due to lower threshold values of the mounted accelerometers, LSV data could not be compared with the mounted accelerometers' data. However, the future work includes the change of threshold value and conduct the experiment at full scale considering the entire bridge.

Acknowledgements

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Moisture monitoring throughout the construction and occupancy of mass timber buildings

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Abstract:

While wood has been used as a building material for millennia, “mass timber” buildings have only been realized within the past few years within North America. Mass timber refers to a class of wood composites that include glue-laminated timber (glulam), structural composite lumber, and cross laminated timber (CLT). These composites allow multi-story residential and non-residential buildings to be constructed more efficiently than traditional light-framed wood systems. While there are a host of environmental and other benefits to building with mass timber, these buildings are different from steel or concrete buildings as the physical and mechanical properties of wood change with its moisture content. Wood-moisture interactions can lead to difficulties in the utilization of wood such as dimensional instability, cracking, microbial attack, and fastener corrosion. Understanding the amount of moisture and range of moisture fluctuations that could be expected in North American mass timber buildings is necessary for more informed design of mass timber buildings.

This paper presents preliminary findings from an ongoing research program instrumenting CLT buildings to measure wood moisture content. An overview of the research program is presented along with data from first year of moisture monitoring in an 8-story building in Portland, Oregon. This project measures the wood moisture content throughout the construction cycle, including the fabrication, shipping, staging, and erection of the panels. These preliminary field measurements can help characterize moisture changes in CLT during construction and guide the construction of future CLT buildings.

Keywords:

Cross laminated timber (CLT), wood, moisture monitoring, construction

1. Introduction

“Mass timber” buildings made of large timber products such as glue-laminated timber (glulam) and cross laminated timber (CLT) have recently been introduced in Canada and the United States as a way to sequester carbon and achieve taller buildings than are possible with traditional wood systems [1, 2]. Because the timber members in mass timber buildings are much thicker than traditional dimensioned lumber used in “stick frame” construction, they are more fire resistant, but at the same time they pose a challenge in moisture control of the building as they take longer to dry if they get wet [3, 4].

While there have been laboratory and modelling studies of moisture movement in CLT [5, 6], CLT behavior cannot be fully understood without gathering data from real buildings [7]. Data collected on real buildings can be used to validate design assumptions used. Because CLT can take a long time to dry out if it gets wet, it's important to understand what moisture exposures the CLT experiences on the jobsite, what the starting moisture content of the CLT panels are when the building is finished, and how quickly the CLT reaches an equilibrium with its environment. This paper describes a portion of a large study to obtain moisture monitoring data in mass timber buildings across several different climate zones in the US. The goal is to understand the wood moisture content from

the factory to occupancy of the building. The focus of this paper is on the challenges of instrumenting and moisture monitoring during the fabrication of the CLT panels through the building occupancy.

2. Methods

Overall, the approach for moisture monitoring involves sensors installed at the CLT production facility, and additional sensors on the jobsite at different construction stages. This paper focuses on the sensor installation in the first building, an 8-story building in Portland, OR. The monitoring project utilizes small, pin type moisture meters manufactured by Omnisense LLC (Models no. S-2, and S-16). The meters calculate wood moisture content by measuring the electrical conductance between two pins embedded in the wood [8, 9].

The installed sensors in the building are located in five primary assemblies: (1) glulam columns near the wood/concrete foundation interface (2) CLT- sensor installed at the top with pins measuring at the half depth and full depth (3) CLT- sensor installed at the top with pins measuring at each lamination within the CLT (4) CLT- sensors installed at the top with pins measuring the top lamination (used only on the roof) (5) sensors installed in fire-retardant-treated (FRT) stud walls to measure the moisture content of the secondary

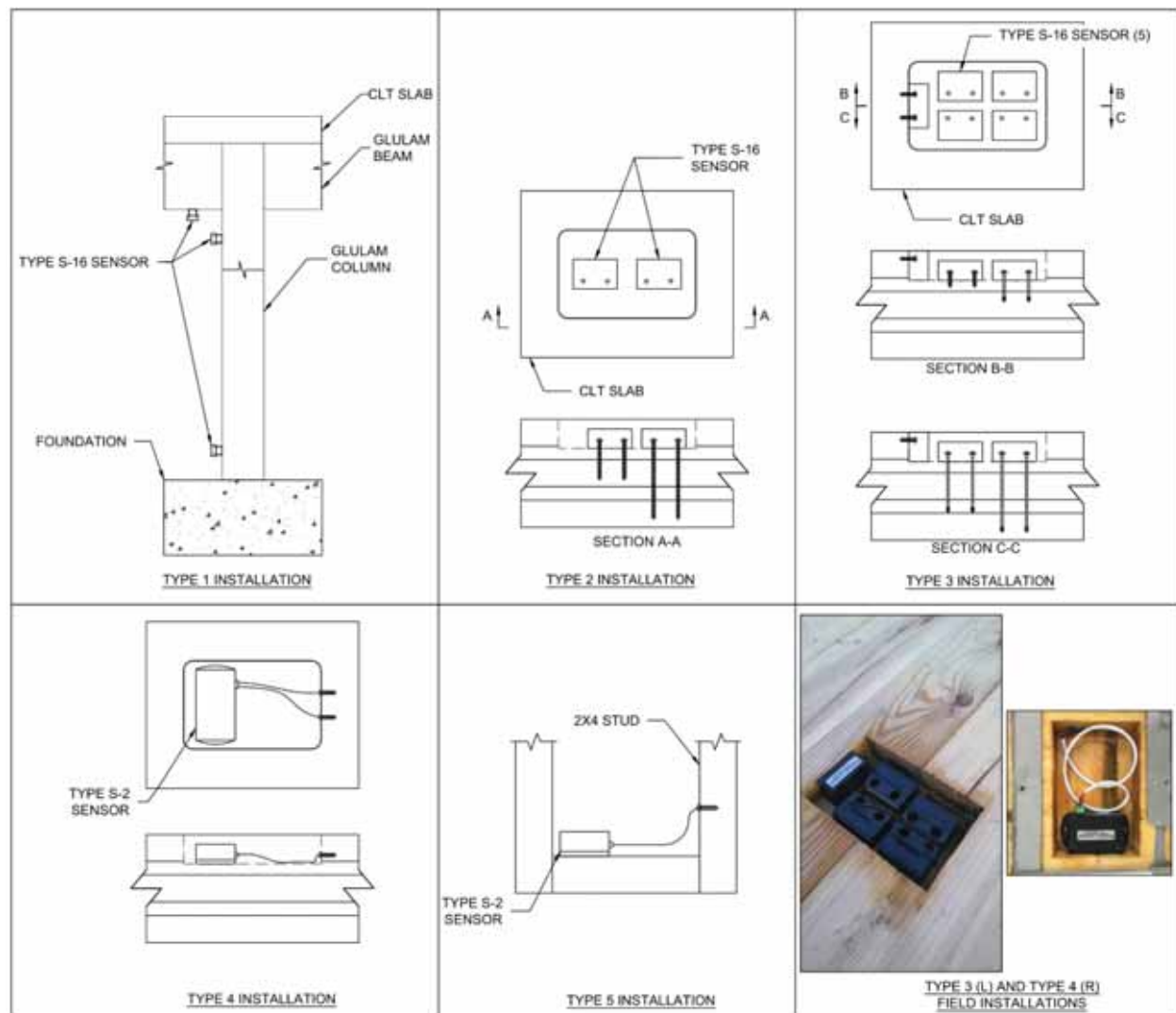


Figure 1 : Sensor installation details

structure. Figure 1 shows the various measurement configurations. Because the building owner preferred the sensors to be hidden from view, sensors were installed on the top side of the CLT panels. This required notching out small areas to place the sensors. Overall, eighty three sensors were installed throughout the building.

Twenty of the sensors were installed at the Structurlam factory located in Penticton, British Columbia, Canada on November 18-20, 2016. Four panels were installed with five, type S-16 sensors (type 3 configuration). The panels chosen for production monitoring were selected on a basis of availability and accessibility within Structurlam's production cycle. Sensors were installed in the panels to record data during storage at Structurlam and through shipping and arrival at the building site.

The remaining 63 sensors were installed in two stages as building construction progressed on site during the building's construction.

The first set of sensors were deployed upon the completed framing of the fourth floor on January 6–8 of 2017 and included all sensors on the fourth floor and below. At the same time, a wireless gateway was installed to retrieve and transmit the data from the sensors. However, in the days following the January implementation trip the project site was subjected to adverse weather conditions including a rare blizzard and frequent precipitation. During this time, the building's framing was fully exposed to environmental conditions without a building enclosure. This direct exposure to liquid water damaged many of the sensors. Even though sensors installed in recesses in the top layer of the CLT were covered with flashing and were sealed with tape after installation to protect them from liquid water, this system was ineffective and many of the CLT integrated sensors on the site were damaged by precipitation.

The second set of sensors were installed on February 10–13 of 2017 upon the completed framing of the

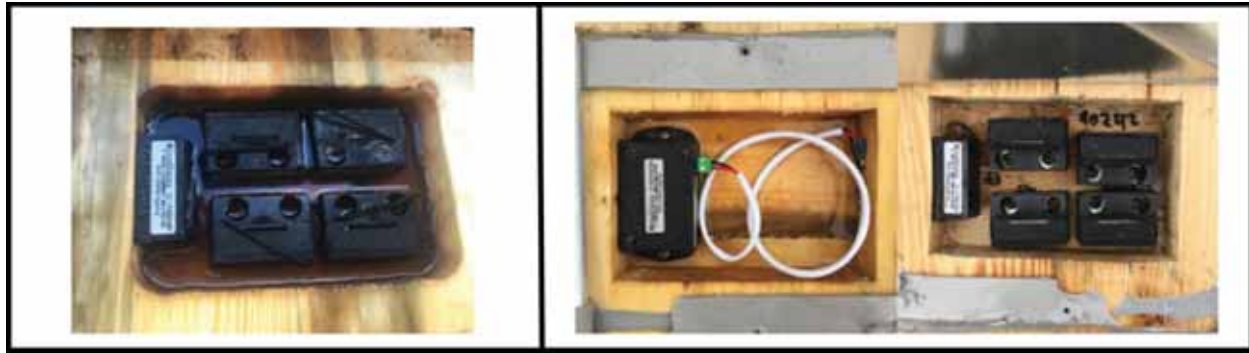


Figure 2 : Water damaged sensors from the first (left) and second (right) installations.

structural system up to and including the roof. In addition, damaged sensors installed on the prior implementation trip were removed and replaced. All sensors placed in recesses on the top of the panel were covered with flashing and sealed with foam gasketing and silicone caulk.

At the time the sensors were installed, it was expected that the roofing membrane would be installed immediately after. However, heavy precipitation followed the sensor installation before membrane application. Due to concerns with drying ability of the rooftop CLT panels, the installation of the water impermeable membrane on the top side of the CLT panels was delayed. During this period, several of the recesses containing sensors became waterlogged and the sensors were damaged. Figure 2 shows pictures of water damaged sensors on the site

3. Results and discussion

The goal of this paper was to describe the approach for sensor installation, and share lessons learned for future moisture monitoring of mass timber buildings under construction. At this point, the two major findings are that (1) CLT panels remain dry in the factory and throughout the shipping process and (2) without robust sensors that can withstand adverse environmental conditions, it is extremely difficult to collect data throughout the construction cycle before the building envelope is finished.

Figure 3 shows the wood moisture content during the manufacturing and shipping stages of the construction process. The sensors were installed on November 20th, 2017 in panels that would be placed on the fourth floor. The panels were erected on January 5th, 2017. Note that wood moisture content remains between 10% and 15% MC throughout the fabrication, shipping, and initial construction. There is a large spike in the moisture content readings in the middle of January, due to a precipitation event during construction where the sensors were exposed to liquid water causing the sensors to short out. Thus, Figure 3 shows no post-construction data since the sensors stop working. Because the moisture content is based upon the measured resistance, bridging (shorting) of the moisture meter pins by liquid water results in a high

effective moisture content reading. These high moisture contents, in all five layers, were likely caused by a liquid water current path at the moisture meter pins. The liquid water also caused the circuit board to short which damaged the sensor.

Figure 3 also highlights the difficulties of trying to perform moisture monitoring during construction before the building envelope is finished. Of the 83 sensors installed, 35 stopped working because of water damage. The sensors are not waterproof and there is a high likelihood of the sensors getting wet during construction. Furthermore, since the sensors were placed within recesses on the top sides of panels, water managed to wick into these recesses and damage the sensors despite the waterproofing methods employed.

Figure 4 shows data from the glulam columns on the first floor near the concrete footing. Similar to the CLT panels (Figure 3), the data show that the moisture content of the columns were high during construction. However, because these sensors were installed on a vertical face of the wood, they were not exposed to water ponding and were able to continuously transmit data throughout the construction cycle. It can be seen that glulam columns dried out quickly after construction and have been maintaining a steady moisture content slightly above 15% MC.

4. Lessons learned

Based on the results from this study, we recommend the following in future monitoring projects:

1. Sensors should be protected by placing them on the bottom side of the panel to create a built-in "roof" for the sensors and prevent ponding of water in the sensor recesses.
2. Sensors should be placed in waterproof boxes with only wires running out to the moisture meter pins. However, even with an improved approach for protecting sensors from water, it is unlikely that all of the installed sensors will survive the construction phase of the project and continue to work throughout the occupancy phase.

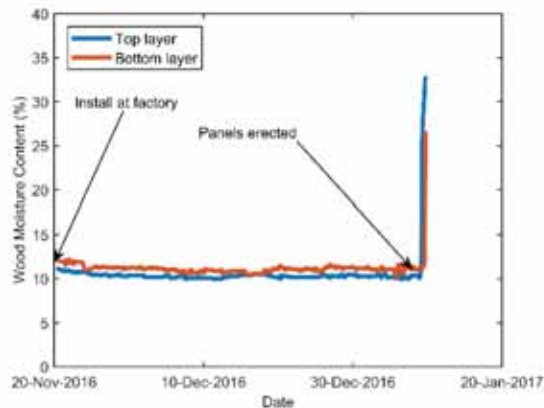


Figure 3: Wood moisture content during fabrication, shipping, and installation.

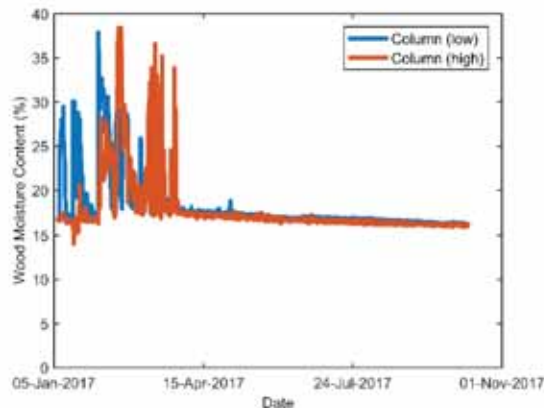


Figure 4: Wood moisture content of the glulam columns on the first floor. “

5. Conclusions and outlook

The goal of this project is to collect real-world data on the hygrothermal performance of mass timber buildings over several years. Currently, the sensors have been installed and data was collected during the construction phase. Based on sensors readings CLT panels remain dry during the fabrication and shipping phases. Although a complete understanding of the moisture behavior of the building throughout occupancy is not yet available, this paper lays out valuable lessons about how difficult it is to install moisture monitoring equipment during the construction phase, which has inspired designs for more durable instrumentation approaches.

Acknowledgements

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The application of major road infrastructure to support and drive sustainable urban mobility

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Abstract:

The Aberdeen Western Peripheral Route (AWPR) is a major 58km roads infrastructure project with funding partners including Transport Scotland, two local Municipal Authorities and the Scottish Futures Trust. The project aims to have significantly positive impacts on congestion, economic growth, safety and, crucially, a lowered regional impact on the environment.

These environmental benefits are predicted specifically to impact on traffic emissions (due to an improvement in the free flow of traffic) and improved air quality in urban areas, with this carrying the potential to assist with the implementation of pedestrian and cycle friendly interventions in Aberdeen itself. Local studies have sought to explore how the city and region can plan to 'lock in' these benefits, through a range of projects concentrated on changes in modal split between transport methods, and support for organisations and individuals to enact change (through shared transport, for example). The use of smart technology and planned freight movement also requires careful management.

This research concerns the ways in which the implementation of such a major infrastructure project can be regarded as holding potential to support the introduction of associated sustainable mobility interventions. In that sense, the research aims to explore how the AWPR might be regarded as being part of a wider greening of transport in the region. The research also explores how this must be planned and implemented in a context where the associated sustainable mobility projects are central to realising these 'green' benefits, with a commitment to ensuring that associated social and economic benefits can lead to improvements in quality of life. Current initiatives are detailed, with a critical discussion of their implementation and planned or anticipated impact.

Keywords:

Mobility, infrastructure, cities, emissions, quality of life

1. Introduction

The planning and implementation of major infrastructure to meet environmental goals can immediately offer potential through the measures themselves, as well as through the impact which works are likely to have on affected areas. The Aberdeen Western Peripheral Route (AWPR) is a major 58km roads infrastructure project with funding partners including Transport Scotland, two local Municipal Authorities and the Scottish Futures Trust. The project aims to have significantly positive impacts on congestion, economic growth, safety and, crucially, a lowered regional impact on the environment.

The region has experienced an incremental growth in vehicular traffic over a number of decades, and this can be associated with both private personal transport and industrial freight. Since the 1970s, the area has seen massive economic growth through the discovery of offshore oil reserves and the subsequent establishment of large scale indigenous on-land facilities. The harbour of Aberdeen itself is located in the city centre, and has numerous support operations associated with the oil and gas industry. This means that a desire to somehow direct freight and other industrial traffic around and away from the city centre

is problematic, and requires creative solutions including the implementation of innovative technologies. Nevertheless, levels of traffic congestion in the city centre are high, with levels of air pollutant in contravention of EU regulations. The city and region have aspirations to make a transition to a point where the perceived and actual quality of life for residents is improved, partly through support for increased levels of safe and enjoyable cycling and walking.

Predicated on the assumption that the AWPR does not induce additional travel demand, the anticipated environmental benefits to accrue from the AWPR relate specifically to: (i) a positive impact on traffic emissions (due to an improvement in the free flow of traffic); and, (ii) improved air quality in urban areas. With planning and support for intervention measures, it is predicted and planned that the city and region will be able to realise the potential to assist with the implementation of pedestrian and cycle friendly initiatives in Aberdeen itself. Local studies have sought to explore how the city and region can plan to 'lock in' these benefits, and hence avoid induce more demand for travel, through a range of projects concentrated on changes in modal split between transport methods, and support for organisations and individuals to enact change (through shared transport, for example). The use of smart

technology and planned freight movement also requires careful management.

This research concerns the ways in which the implementation of such a major infrastructure project can be regarded as holding potential to support the introduction of associated sustainable mobility interventions. In that sense, the research aims to explore how the AWPR might be regarded as being part of a wider greening of transport in the region. The research also explores how this must be planned and implemented in a context where the associated sustainable mobility projects are central to realising these 'green' benefits, with a commitment to ensuring that associated social and economic benefits can lead to improvements in quality of life. Current initiatives are detailed, with a critical discussion of their implementation and planned or anticipated impact.

1. Context for the AWPR

a. History

The original concept of a peripheral route for Aberdeen, a city bypass that would link the A90 trunk road to the north and south of the city with the A96 route to the west, was first developed in the 1950s [1]. However, it was not until more than 50 years later that a focused response was applied to the design and build of a peripheral route for Aberdeen.

In 2001, the North East Scotland Transport Partnership (NESTRANS) was established as a voluntary non-statutory regional transport partnership between Aberdeen City Council, Aberdeenshire Council, Scottish Enterprise, and Aberdeen and Grampian Chamber of Commerce. The purpose of this voluntary partnership was to facilitate the parties working together to address transport challenges within the region and to develop appropriate strategy. It was under the auspices of NESTRANS that a 2003 report, *Delivering a Modern Transport System for North East Scotland*, was produced detailing a number of schemes for the region. One of these schemes was the AWPR, the intention of which was to:

enable through-traffic to bypass Aberdeen, which in turn allows for prioritisation for buses, cycles and pedestrians within the urban area. It also improves peripheral movements around the City, improving access to Park and Ride sites and relieving heavily-used, unsuitable rural routes. It will improve accessibility to existing and planned employment locations and open up possibilities for future land release. Finally, it will transform accessibility of freight and business service movements to and from the north and west of Aberdeen [16].

Following a number of years of development, a preferred route for the AWPR was identified in 2005. After the conclusion of a Public Local Inquiry in 2009, and the resolution of a protracted legal battle in 2012, the award of Scotland's largest Non-Profit Distributing contract was made in December 2014¹.

The AWPR will consist of mainly a new two-lane dual carriageway in each direction, combining a bypass for longer-distance traffic while allowing for shorter journeys and thus removing traffic from unsuitable rural and local urban roads [22]. The route taken by the AWPR can be seen in Figure 1 below.



Figure 1: Copyright Transport Scotland

In addition, the AWPR must also be viewed within the context of several concurrent policy initiatives operating within the City: (i) the City Centre Masterplan (CCMP); (ii) the Local Transport Strategy (LTS); and, (iii) the Sustainable Urban Mobility Plan (SUMP); and

¹ The non-profit distributing (NPD) contract model was developed and introduced as an alternative to the traditional private finance initiative model in Scotland.

the participation of Aberdeen City Council and local partners in the European funded Horizon 2020 research project CIVITAS PORTIS. Each of these separate issues will be discussed in further detail below.

b. City Centre Masterplan

The CCMP is a 25-year plan for the city that also contains four major transportation projects, with the goal of increasing pedestrian priority in the city and “delivering a greener, safer, healthier, better-connected city centre” [8].

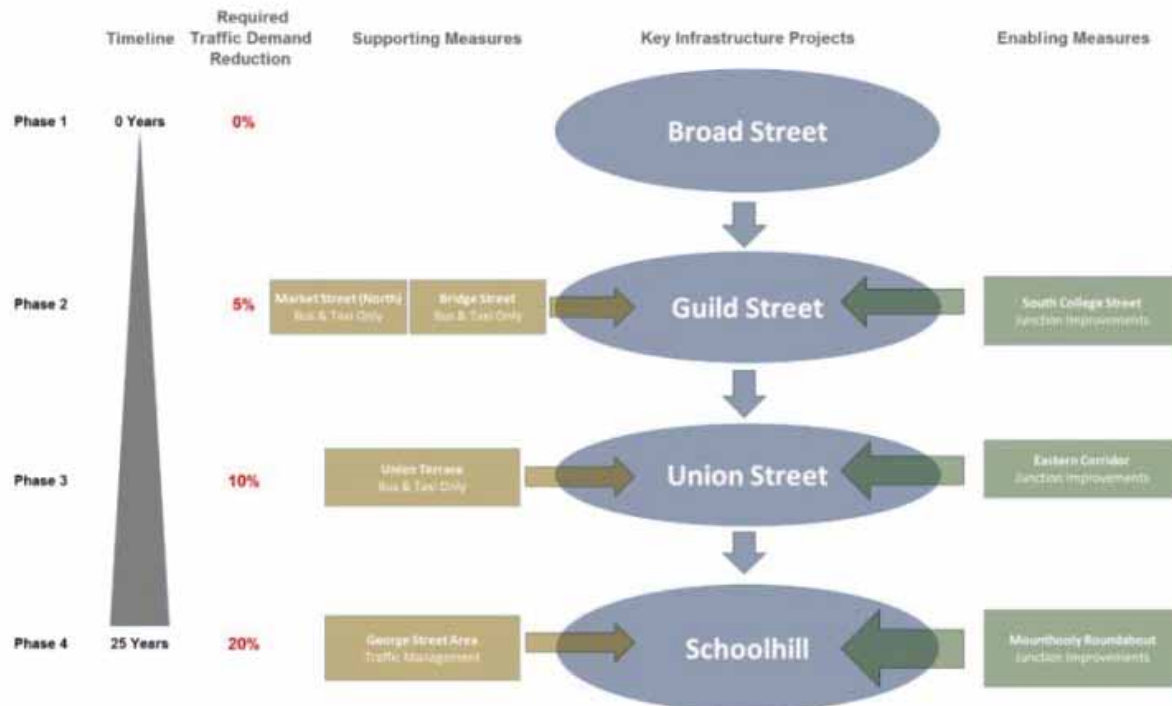


Figure 2: Pedestrian priority in CCMP (Copyright Aberdeen City Council 2017)

Aberdeen City Council state that in order to deliver the City Centre Masterplan in its entirety, traffic levels in the city would require to be reduced by one fifth [8]. It is anticipated that the AWPR will assist in achieving the objectives set out in the CCMP, for example, by removing the 30% of traffic passing through the city centre [8].

c. Local Transport Strategy

The current iteration of the Local Transport Strategy (LTS) for the city (2016-2021) focuses upon the delivery of outcomes that will “lock in” the benefits of the AWPR [6]. It has a broad philosophy of creating a “sustainable transport system that is fit for the 21st century, accessible to all, supports a vibrant economy, facilitates healthy living and minimises the impact on our environment” [7]. The LTS draws on EU (*EU White Paper on Transport*), national (*National Transport*

Strategy) and regional (*Regional Transport Strategy*) policy documents in order to deliver the city’s transport priorities within the context of a wider policy framework. It is optimistically suggested that by 2021, the transportation system will have developed the capacity to deliver the following outcomes: (i) increased modal share for public transport and active travel; (ii) reduced need to travel and reduced dependence on private vehicles; (iii) improved journey times and reliability across all modes; (iv) improved road safety; (v) improvements to the air quality and environment; and (vi) improved accessibility to transportation for all

citizens [6].

It is perceived that the AWPR is key for the city during the timeframe the LTS is in place, specifically in relation to the new opportunities that this new infrastructure affords and the ability to reorganise and reprioritise the city’s roads network [6]. Thus ‘locking in’ the benefits of the AWPR is very much at the core of the LTS.

The AWPR also allows the Council an unparalleled opportunity to revise the operation of the transport network in the City, through the Roads Hierarchy Study, with options to utilize the freed-up capacity anticipated on many routes and to prioritise the movement of sustainable modes of transport. It will also facilitate the delivery of many of the City Centre Masterplan projects and its associated transport masterplan, the Sustainable Urban Mobility Plan. [6].

Therefore, when looking at the CCMP, the LTS and the SUMP collectively, it is apparent that a number of policies exist within the city aimed at improving the

sustainability credentials of the transportation network. However, Aberdeen has suffered from what is credited as an “inability to delivery on a low carbon agenda” [12] due to the city’s failure to “manage the game” so that within Aberdeen there are sufficient influential voices to support “a wider politics of mobility that took low carbon policies really seriously.” [12]. This deficit is highlighted by reception of a survey conducted into road user charging that featured in the 2003 NESTRANS report [16]. Further scrutiny of the idea by the local authority was halted due to significant opposition from the local print media.

Furthermore, it has been noted that the “mainstreaming of the low carbon agenda” in Aberdeen is “often simply seen by politicians as a straight vote loser” [12]. Furthermore, the importance placed on the AWPR, as can be seen within the context of the CCMP and LTS, has resulted in a transportation debate that has been distorted so that, “A consistent narrative emerged whereby the local authority’s proposed policies seeking to manage traffic (to the benefit of more sustainable modes) were painted in the media as ‘anti-car’” and that “...politicians have increasingly regarded such policies with suspicion due to the opprobrium they attract.” [12].

d. CIVITAS PORTIS

CIVITAS PORTIS is a Horizon 2020 initiative involving five European cities:



Figure 3: Map of participants in CIVITAS PORTIS (Civitas Initiative 2016).

The intended purpose of the project is to demonstrate that both function and social cohesion between city centre and ports can be increased through sustainable mobility [10]. It is anticipated that the project will: (i) improve government for enhanced co-operation between cities and ports; (ii) create more sustainable and healthier city-port environments; (iii) shape more integrated transport infrastructure and mobility systems; and (iv) improve the efficiency of urban freight transport [10].

CIVITAS PORTIS commenced in September 2016 and will conclude four years later in September 2020. With the AWPR due to be completed in late 2017/early

2018, the project coincides with a significant change in transportation in Aberdeen and the surrounding region. It has been noted that such European programmes are a “vital mechanism” in the promotion of a sustainable transport agenda in the absence of coherent funding structures and this has particular significance due to the restrictions on infrastructure investment and limitations on council tax rises in Scotland [21]. Therefore, CIVITAS PORTIS presents a unique opportunity for the city region to trial and implement complimentary sustainable transport policies that will ensure the benefits of the AWPR are indeed “locked in”. Critically, CIVITAS PORTIS provides the opportunity for capital spend on infrastructure improvements thanks to the level of funding that has been allocated under the project. The local authority is therefore not relying on annual budget allocations from within their own revenue constraints to fund what may be considered unpopular initiatives, due to their “green” credentials.

2. Predicted environmental benefits (targets)

It has been suggested that local authorities in the UK have a window of opportunity within the low carbon agenda context and that “links between institutions, communities and individuals are critical in carving our more sustainable pathways” [11]. This “window of opportunity” is also apparent within the bounded context of the AWPR and the potential window offered by the creation of new transport infrastructure to allow space to be reclaimed within the region for active and sustainable modes of travel. Similarly, it is also important that institutions, communities and individuals are involved in this “greening” process, for understanding the psychology of travel behaviour in citizens is a key factor in encouraging modal shift [13] [21].

Despite a concern that the increased connectivity across the region may result in increased road travel as the result of further dispersal of homes and business [18], there have been a number of predicted environmental benefits identified as a potential consequence of the AWPR routing traffic away from roads in the region. Broadly, these range from a carbon benefit derived from a reduction in emissions, more space for active modes of travel and increase uptake of public transport due to improvements in journey times. In the 2008 “Locking in the Benefits” study undertaken on behalf of NESTRANS, it was observed that,

More public transport priority and further development of schemes to promote more efficient and effective travel will go further and enhance the AWPR benefits and address some of the more pressing objectives identified in relation to the environment. The integration of environmental benefits from the AWPR can be captured and sustained with those forms of complementary measures made possible by reductions in traffic flow on key existing routes and accompanies by a

release of major benefits to the economy, safety and accessibility.[17].

Prioritising public transport and ensuring the integration of these environmental benefits is important to ensure that the immediate benefits of the AWPR are not negatively impacted upon by dispersal of homes and businesses and the associated additional car travel [18].

Furthermore, from the perspective of national climate change targets, the importance of local government to the delivery processes of sustainability policies has been described as a “key medium through which to coordinate and influence workable local level responses to the problem of developing more effective policies around energy and environmental issues” [11].

a. Walking and Cycling

Current statistics on modal share for Aberdeen City and Aberdeenshire indicate that the capacity exists for encouraging more citizens out of their cars into either active or sustainable transportation modes:

	All Trips (% mode share)		
	City	Shire	Scotland
Car	60.3	79.6	64
Bus	11.8	4.6	10
Train	0.1	0.9	2
Cycle	0.9	1.4	1
Walk	26.0	12.7	22
Other	0.9	0.8	1

Figure 4: Current modal share for Aberdeen City (City) and Aberdeenshire (Shire) (Scottish Household Survey 2015)

Research shows that it is estimated that physical inactivity results in around 2,500 premature deaths in Scotland each year, costs the NHS approximately £91m and represents the second biggest cause of mortality [19]. Technology, urbanisation, sedentary work environments and increasing car use are all cited as reasons for the decline in physical activity in Scotland [19]. Therefore, successfully promoting walking and cycling as a mode of active travel holds both the potential for environmental and health benefits for the region through reduction in congestion, reduced carbon emissions, improvements to air quality and general improvements to health and wellbeing [20].

It has been observed that one of the main differences between Scotland and other countries with higher levels of cycling, is the lack of connected cycling infrastructure [20]. However, it is not only the lack of cycling infrastructure which needs to be addressed, improving the walking network, including the prioritising of path and footway surface conditions, could also potentially result in significant modal shift [20]. Therefore, it is significant that one of the measures identified for implementation under the CIVITAS PORTIS initiative is one focussed on “Fostering

Walking and Cycling”. It is anticipated that the city’s participation in CIVITAS PORTIS will enable the prioritisation of walking and cycling to realise the environmental and health benefits of active travel. The approach adopted by the local authority will combine infrastructure improvements along with public information campaigns and, if achieved, will contribute significantly to the wider ambition of “locking in” the benefits of the AWPR.

b. Public Transport

As noted above, one of the objectives contained within the LTS is that by 2021, there should be more journeys taken by public transport. This replicates the similar policy strategies identified by both the *Regional Transport Strategy* and *National Transport Strategy* and also by the CCMP and SUMP which both identify public transport as being key to the success of the city centre.

However, a number of barriers have been identified in both the LTS and the *Regional Transport Strategy* in relation to public transport usage, these include (i) quality of service (frequency, reliability, capacity and comfort); and, (ii) value for money. A Bus Quality Partnership Agreement (the **Agreement**) is currently in place for the region, which aspires to address some of these issues by:

- Increasing bus use by raising standards and meeting targets set out in the Agreement;
- Helping to reduce traffic levels and particularly to reduce congestion; and,
- Helping to increase social inclusion by developing a good value, accessible bus network

In order to achieve the sustainability objectives as set out in the raft of policy documentation for the region, it is apparent that working with the bus operators will be an integral part to achieving a modal shift in favour of public transportation. From a service quality perspective, it is acknowledged that “For bus patronage potential to be fully realised, it is essential that the image that the bus currently presents and the performance it delivers is enhanced.” [18]

There are many related benefits to ensuring that bus patronage does indeed increase. Not only will competitive pricing have environmental benefits, there are social advantages to addressing the issue of high public transport fares. Specifically, better access to buses can assist in addressing issues of social exclusion and access to key services [6] and also in providing access to education and social opportunities for young people [18] all of which are of socio-economic benefit to the wider region.

c. Scotland’s Carbon Reduction Strategy

The ambition to tackle climate change is central to the Scottish Government’s aspirations for the economy.

Following the introduction of the Climate Change (Scotland) Act in 2009, it was established that greenhouse gas emissions would be reduced by at least 42% by 2020, with a view to achieving an 80% reduction by 2050² [2].

authorities (Aberdeen City Council and Aberdeenshire Council), sought to investigate "Locking in the Benefits" of the AWPR. The report notes that the purpose of "locking in the benefits" is to ensure that both the objectives and the benefits of the AWPR are met [17]. Using a process of desktop analysis of existing studies and relevant documentation, the study identified a

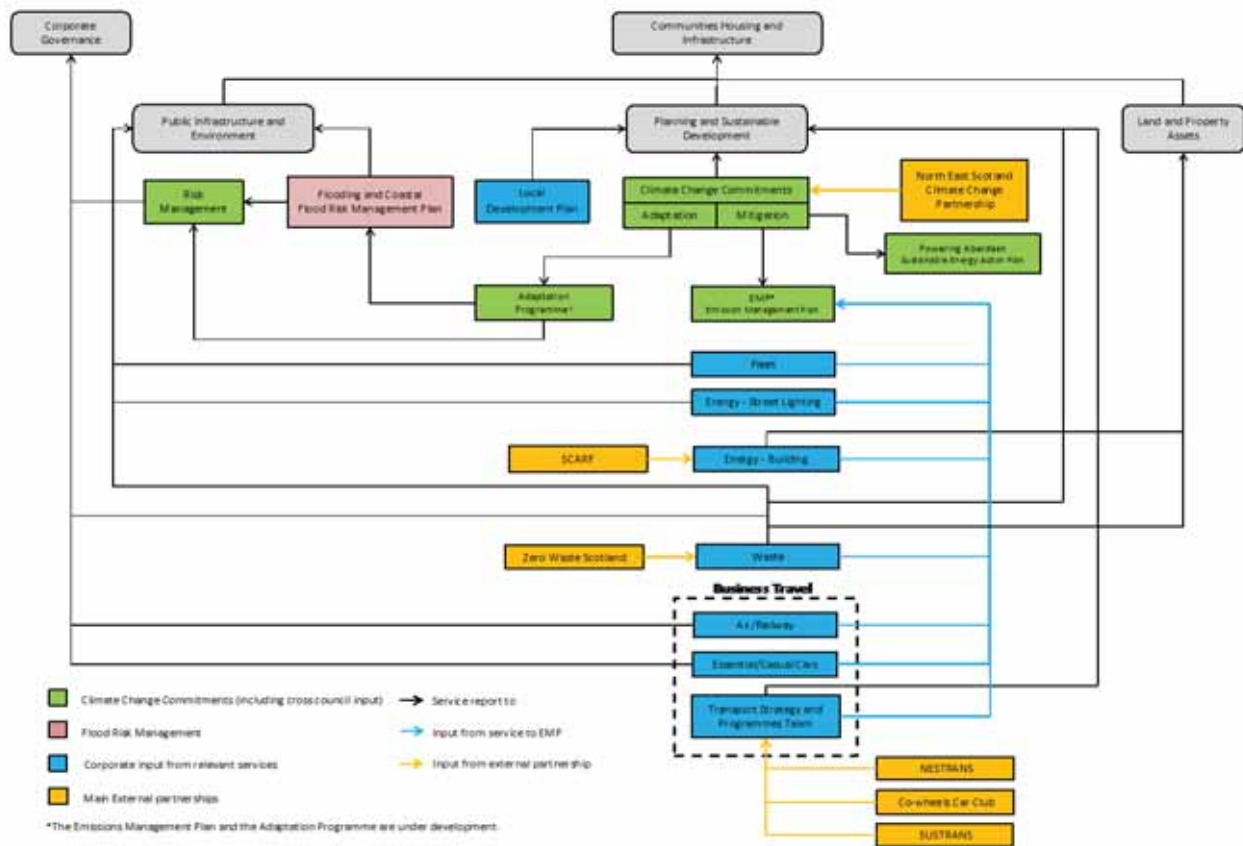


Figure 5: Climate Change Management Strategy, Aberdeen City Council 2015-2016

Furthermore, all 32 local authorities in Scotland have signed Scotland's Climate Change Declaration which commits them to mitigating their impact on climate change, thereby tackling climate change at a local level [14]. In addition, each local authority is required to complete annual Climate Change Reports. Details on how Aberdeen City Council manage their climate change action is detailed in Figure 5 below:

3. Locking in the benefits

a. NESTRANS 2008 Study

A comprehensive study undertaken in 2008 identified the AWPR as holding the potential for effecting a significant impact on the road network within the North East of Scotland. This study, undertaken by NESTRANS, with the support of the two local

number of sustainable travel improvements and potential schemes that could benefit from the existence of the AWPR. Focussing mainly on improvements to public transport, it was noted that, "These schemes now require further detailed investigation, planning and design within a timeframe relative to the AWPR to achieve the best possible mode shift and greatest carbon benefit." [17], although there is little evidence of significant improvements in the nearly ten years since the report was produced.

b. "Green" Benefits to Major Infrastructure

It has been suggested that the concept of sustainable development should be viewed as something which frames a problem, rather than as something that strictly

² When compared to the 1990 baseline for carbon dioxide, methane and nitrous oxide, and a 1995 baseline for

hydrofluorocarbons, perfluorocarbons, sulphur hexafluoride and nitrogen trifluoride

defines the problem [24]. Indeed, it is a concept that is developed through the pressures and problems faced by decision makers [23] and that, in Scotland, is now regarded by the Scottish Government as being critical to policy development [15]. Therefore, there is an onus on local authorities to not only develop but, in order to mitigate the impacts of climate change, effectively “frame” policies to address the sustainability problem and to influence how citizens think about travel and the sustainability implications of those travel choices.

Indeed, current literature suggests that a change in the “beliefs, values and ideas held by citizens in respect of the kind of society that is ultimately desired” is required and that in order to achieve this shift, and that there is a need to foster a “greater political will to act, which will inevitably involve making some hard choices in relation to overhauling current systems of production and consumption, decision-making processes, and institutional arrangements” [11]. The AWPR is an example of how by framing the AWPR within a sustainability context, politicians can be encouraged to consider the future sustainability of a car-oriented society and how to make these hard choices for the benefit of both citizens and the environment. However, it is conceded that the current political composition of the local authority creates a situation whereby making hard choices in a marginal political landscape is problematic. Therefore, an element of caution may be required in settling the AWPR within a sustainability context at the risk of it being perceived as ‘greenwashing’.

4. Sustainable Urban Mobility Plan (SUMP)

Aberdeen City Council developed a Sustainable Urban Mobility Plan during 2012-14, which connected with numerous sustainable mobility initiatives in the city at the time, including involvement in the Interreg North Sea ‘CARE North’ project, and the development and implementation of a fleet of hydrogen powered buses. The plan was regarded as being a vital part of green infrastructural development in the City, as it would help to support both economic growth and the implementation of a people-focussed city centre masterplan. As noted earlier, Aberdeen also contains areas where air quality indicators exceed acceptable EU limits, and proposed actions within the SUMP aimed to address these issues. The SUMP also recognised that Aberdeen contains a working industrial harbour in the city centre, meaning that consideration of mobility must take into account both personal and freight vehicles. The SUMP was selected as a suitable method to present and develop ideas and propose solutions as it allowed the city to link urban planning and mobility concerns, as well as recognising a wider and well establish European agenda (with examples,

case studies and precedent). With this in mind, one can note that a successful SUMP will:

- ensure the transport system is accessible to all
- improve the safety and security of its users
- reduce air and noise pollution, greenhouse gas emissions and energy consumption
- improve the efficiency and cost-effectiveness of the transportation of people and goods
- enhance the attractiveness and quality of the urban environment

The SUMP was developed in consultation with the public, and involved a project delivery group which brought together the local authority, regional transport groups and local academic experts [3][4][5]. In terms of transport modes and the network existing in Aberdeen city centre, the plan considered pedestrians, cyclists, car parking and access to transport (including routes). Crucially, the plan also considered how these might interact with urban design issues, including areas of shared space (semi-pedestrianised zones) and the designation of key traffic routes. It can be noted that a further definition and establishment of a roads hierarchy forms a key part of PORTIS itself, and is regarded as a method to help support a transition towards lower carbon mobility in the city.

The plan won the European Commission SUMP award for 2012, where specific mention was made of the role of citizen engagement in its development³

Bearing in mind that this established the SUMP as a core strand of future development in the city, CIVITAS Portis includes specific actions which deal with a refinement of the plan itself, and the enactment of measures which begin to address both freight and personal mobility. In terms of extending the SUMP, the project will consider how best to include a new harbour (under construction) at Nigg Bay, outside of the city centre, and it how relates to movements in city centre as well as main transport corridors. The SUMP is also to be extended to incorporate the ‘North Dee’ area, which forms a zone within the city adopted masterplan. This activity connects with a desire to maximise the potential to foster walking and cycling through the completion of projects undertaken as part of the rolled-out masterplan, and will include consideration of initiatives including cycle hire schemes, and a focus of journeys under 5km⁴.

This mention of the new harbour is crucial, and connects with the major changes which will be realised in the local area as a result of both this and the development of the AWPR. The SUMP, and actions which will be realised in the coming years, relies on their being a hierarchy of roads, and an embedding of

³<http://www.eltis.org/discover/news/aberdeen-wins-european-commissions-first-sump-award-0>.

⁴ See, for example, ‘no ridiculous car journeys’ campaign in Malmo: <https://exploring-and-observing-cities.org/2013/05/25/malmo-no-ridiculous-car-journeys/>

sustainable mobility principles, in future planning and development. In this sense, it can be regarded as a mechanism through which the 'green infrastructure' potential of the AWPR can be secured.

5. Conclusions and outlook

This research has set out a framework within which it has been possible to consider the effects of a large-scale roads building programme in the context of wider positive environmental impact. This requires the development and implementation of a range of specific measures, which will be applied during the period 2017-2020. The conclusions which can be drawn from the current regional developments concern mainly the opportunity to design and deliver localised benefits as a result of the displacement of traffic from the urban centres. Nevertheless, there is no good reason to believe that the building of new roads will lead solely to a displacement of traffic, but rather that there is an associated need to embed the potential benefits of that displacement in planning and management of inner urban areas.

This has slightly different yet associated implications for personal and freight movement. With regards to personal mobility, the city and region has aspirations to support walking and cycling in the city centre, but has limited plans for the development of cycling as a longer-range mobility option (as is common in many Scandinavian countries). However, the local sustainable urban mobility plan will be revised to embed the measures and aspirations associated with low-carbon transport and links the major local projects concerning mobility, hydrogen as a fuel and how this may connect with the transition towards a low carbon economy. With freight, interventions already demonstrating results include the use of prioritised traffic flow, thus reducing both fuel consumption and emissions in traffic servicing the harbour. This can connect with associated initiatives along the AWPR itself, and is utilising emerging technology associated with the wider aspirations of Aberdeen regarding digital transformation of city services.

The funded projects associated with this research concern the sustainability, efficiency, local cooperation, integrated transport and low carbon mobility. Whilst it has been interesting to explore the initiatives and measures associated with these in the isolated context of the projects themselves, within Aberdeen itself it has been equally interesting to understand how the development of the AWPR has been presented and planned to act as a catalyst for positive change. In terms of the apparent intention to deliver a relocation of traffic from the city centre, and to reduce emissions from freight through intelligent use of a new roads hierarchy, AWPR appears to carry great potential.

The extent to which the planned initiatives will actually mitigate or compensate for any increase in traffic along the AWPR itself, though, will require monitoring,

evaluation and an ability for the city region to be agile in its response. That the project is connected in terms of both policy and local measures (through PORTIS) perhaps starts to address some of the barriers to change in terms of governance and decision making which have been reported previously, and should enable the city and region to implement initiatives which have appeared in plans for many years.

Ensuring that the city region is able to deliver on a connection between policy, expenditure and delivery of projects will be crucial, though, and demonstrating a genuine connection between plans and action will be a challenge for the city and region.

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Life cycle costing and life cycle assessment of wall systems with different insulation

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ABSTRACT:

Sustainability not only consists of effective protection of the environment but also concerned about social and economic benefits. An integrated analysis is needed to narrow the gaps between environmental and economic requirements of a construction project, and support decision-making. This paper aims to investigate several wall systems with different insulation types and thickness to find cost effective and environmental friendly (two main parts of sustainable design) wall assemblies. Also, the relative importance of initial and operational costs as well as the embodied and operational energies in a building's life cycle, especially in low-energy buildings is studied. In this study a two-storey detached single-family house with 128m² area in cold/hot and mild climate zones, Toronto and Vancouver respectively, are considered. A total of thirty-six wood-frame wall assemblies with single, double and exterior insulation systems are studied. The heating load, cooling load, total energy consumption (Include only heating, cooling, and lighting) and CO₂ emissions (Include only heating, cooling, and lighting) of the buildings with different wall systems are compared and analyzed. Analysis of the results suggests that Cellulose insulation with 132 mm thickness is the best practical choice for the both climates, followed by Fiberglass insulation with 150 mm thickness. In the case of retrofitting a building, exterior insulation retrofits lead to a reduction in environmental impact and initial and operating costs of the building in both climate zones than adopting interior insulation retrofit.

Keywords:

Life cycle costing, life cycle assessment, wall systems, insulations, Life cycle cost

1. INTRODUCTION

Sustainability is one of the most significant current discussions in the construction industry. Sustainable development can be defined as development that meets the needs of the present without creating, producing or prolonging conflicts with the requirements of future generations (Ness et al., 2007). Sustainability not only consists of effective protection of the environment, but also includes social and economic considerations (Burgan & Sansom, 2006; Halliday et al., 2005; Finnveden et al., 2009). It means that the growth of the economy can increase sustainable performance. Sustainable design tools predominantly concentrate on environmental impacts and the capital cost of different decisions. However, there has to date been a little discussion that considers both Life Cycle Costing and Life Cycle Assessment within the same project.

Life Cycle Costing (LCC) and Life Cycle Assessment (LCA) are both sustainable tools, which concentrate on different flows of production and consumption of products (goods and services, product-related assessment). Both LCC and LCA are retrospective and prospective sustainable tools (Ness et al. 2007). In this research, these two methodologies are used for different kinds of wall insulation by focusing on total CO₂ and total costs during their life.

Buildings make the main contribution to the environment, not only by decreasing the running

energy in different stages such as operation and maintenance but also by reducing the embodied energies which include the extraction and manufacturing of various materials and on-site transfer and consumption. It is assumed that buildings can reduce their consumed energies by up to one-third (Insulkar, 2005). A key strategy in the design and construction of buildings are the high thermal efficiency of the constructed building envelope, which limit the use of active space conditioning systems. (J. Morrissey*, R.E. Horne 2010)

The aim of this paper is to investigate several wall insulations of single-family buildings in Canadian climate to find the principle of cost efficient and environmentally friendly design (two main parts of sustainable design) of wall assemblies.

We will also investigate the relationship between Lifecycle Costing and Life Cycle Assessment of different wall insulations to discover a suitable kind and thickness of wall insulation for Vancouver and Toronto. To clarify the relative importance of operating and embodied energy in a building's life cycle, especially in low-energy buildings is the goal of this article.

2. LITERATURE REVIEW

2.1. Life Cycle Costing of building components

In the past, wall insulations were selected based on initial cost. The life cycle costs (LCC) of various options were seldom considered in these projects. For example, one study was carried out to consider both the economic and environmental impact of the design options of a commercial building in Shanghai (Wang et al., 2010). Although the researchers tried to consider the operational cost during the lifetime of choices, they neglected other important aspects of LCC such as discount rate, period life, and end of life values.

2.1.1. Relationship between Life Cycle Costing and the environment

Sustainable factors can affect each other. Environmental impact is not considered in Life cycle costing directly, but it is analyzed in life-cycle assessment (LCA). It can be measured with a variety of tools such as Athena and BREAM, while in theory, the relationship between LCC and LCA isn't apparent, and they do have a relationship in practice. The development LCC tool considers environmental issues initiated in the early 1990s (Gluch & Baumann, 2004). Economic activity is closely related to resource depletion and environmental pollution (Udo de Haes & Heijungs, 2007). While many environmental concerns have a close relationship with cost. For example, reduction of material and energy affects both cost benefits and the environment (da Silva & Amaral, 2009).

Connecting environmental and economic aspects together would help to managerial decision making in the early design stages of urban development. When combining economic and ecological dimensions, they can be claimed to complement each other in residential development. (Miro Ristimäki, et al.2013)

LCC gathers information about durability, performance and end-of-life use of materials. Reducing maintenance and replacement of material can decrease negative impact on the environment and improve economical construction (Gardner et al., 2007). Because less energy and material will be consumed, the impact on the environment will not be as high.

In addition, extending the life of the building will reduce the impact on the environment while also ensuring cost savings (Burgan & Sansom, 2006). Using building materials with a longer service life and which can be easily refurbished efficiently will reduce both costs and negative impacts on the environment. This is because constructing new buildings requires more materials and more energy consumption. Consequently, using materials with a longer lifespan

(Wang et al., 2010). However, other costs exist during the lifetime of a building component that is taken into consideration, such as operation cost, end-life cost, and residual value components. One type of insulation may have less initial cost, but its lifetime costing may be more than other optional insulation.

can improve both the environmental impact and life-cycle costing.

Also, at the end of a building's life, some of the materials can be recycled or re-used, while some of the material will go to landfill. The reusable material has a significant advantage over recyclable materials because returning these materials to the construction industry requires less energy than bringing in new material; it also saves manufacturing energy (Burgan & Sansom, 2006). The consequences are cost preservation as well as a reduction in harm on the environment.

2.2. Life Cycle Assessment (LCA)

Climate change, also called global warming, is a pressing global concern across industries, and the building industry has an impotent role in this issue. Manufacturing relevant materials demand the use of a lot of fossil fuels and require significant energy consumption. The consumption of fossil fuels releases CO₂ and other chemical emissions into the air; these greenhouse gasses create a protective layer in the earth's atmosphere. This layer allows short-wave radiation from the sun to reach the earth and prevents long-wave radiation, which is emitted from the warmed surface, to leave the earth; the consequence of this "greenhouse effect" is the heating up of the planet, or "global warming" (Wigginton & Harris, 2002). Also, operational energy influences the environment and release CO₂, and this should be considered in the design process.

So, in addition to initial costs and life cycle costs, environmental impacts are an important criterion for decision making in projects because different kinds of materials consume energy at different rates. Their emissions are also different.

Both Life cycle assessment (LCA) and life cycle costing (LCC) methods were applied during the energy crisis in the mid-1970s. At first, LCA concentrated on energy balance; later, it focused on energy and mass (including materials and waste)(Steen, 2005). LCA was used simultaneously in the UK, Sweden, Switzerland and the USA (Udo de Haes & Heijungs, 2007). LCA, which has been utilized for building assessment since 1990 (Kashkooli et al., 2010), is a technique for assessing the environmental aspects and addresses the potential environment impacts. It is a tool in which the potential impact on the environment, human health and resources are assessed and analyzed (Finnveden et al. 2009).

The building industry, including housing, takes up 44% of all extracted materials from the earth's biological or mineral resources (Roodman and Lenssen, 1994). One-Third of the total landfill waste stream (Kibert et al., 2001), 25–40% of society's energy consumption (Perez-Lombard et al., 2008), and around 30% of greenhouse gas emissions (UNEP SBCI, 2009). (Bahareh Reza, et al..2014)

Life cycle assessment is necessary for several reasons (Ord, 2008):

- It informs decision makers of the environmental impacts of activities and makes a recommendation for improvements.
- It clarifies the extent to which the product interacts with the environment.
- It provides useful insights into the environmental impacts of human activity.

It is important to clarify the environmental impacts of a variety of options before starting a project in the design phase of a project because the design phase has more influence on the environmental impacts than other phases of the life cycle.(Rebitzer, Ekvall, et al., 2004).

2.2.1. Embodied and operation energy

The total life cycle energy of a building consists of both embodied energy and operating energy. (1) Embodied energy (EE): sequestered in building materials during all processes of production, on-site construction, and final demolition and disposal; and (2) Operating energy (OE): used in maintaining the inside environment through processes such as heating and cooling, lighting and operating appliances.

A building's embodied impact can potentially be concentrated in the substructure, shell, or interiors. While the embodied impacts due to service equipment are small, the cladding material and thickness choices are consistently the most significant, regardless of building design configuration (J. Basbagill*, F. Flager, M. Lepech, M. Fischer 2012)

Embodied energy is used in the processes of building material production (mining and manufacture), on-site delivery, construction and assembly on-site, renovation and final demolition. Current interpretations of embodied energy are quite unclear and differ, and embodied energy databases endure problems of variation and incomparability. Furthermore, there is no reliable template, standard or protocol regarding embodied energy computations that could solve problems related to embodied energy inventories. (Manish Kumar Dixit, et al.2010)

The initial impacts were dominated by operational (use phase) energy consumption. The use phase also served as the greatest source of impact reductions. (Sarah V. Russell-Smith*, Michael D. Lepech, Renate Fruchter, Allison Littman 2014)It was known, until a few decades ago, that operating energy represented by far the largest share of the life cycle energy bill, ranging to about 90–95% even when accounting only for the heating demand. (Sartori *, A.G. Hestnes 2006).Based on the analysis of 60 cases found in literature, operating energy represents by far the largest part of energy demand in a building during its life cycle. (Sartori *, A.G. Hestnes 2006)

In the life cycle of a building, operational energy services (e.g., heating, ventilation and air conditioning, HVAC) usually contribute to approximately 80% of the total energy consumption (Ramesh et al., 2010).

The findings show that the addition of higher levels of insulation in Australia paid back its initial embodied energy in life-cycle energy terms in around 12 years. However, the saving represented less than 6% of the total embodied energy and operational energy of the building over a 100-year life cycle. (Roger Fay, et al.) Thermal insulation has an embodied energy cost, Energy to make the insulation, but savings in operational energy accrues over time.

In general environmental terms the relatively high importance of the initial embodied energy of a building in a temperate climate, as mentioned here, may suggest of that new construction to not be always the best solution. Renovation of an existing building may offer considerable embodied energy and financial savings, with the opportunity to deliver equal amenity and perhaps an improved efficiency. (Roger Fay, et al.)

2.2.2. Differences between LCC and LCA

Neither has the ISO 14040 series of standards for LCA methodology addressed the incorporation of economic analysis with LCA (Gregory A. Norris). Life cycle costing and life cycle assessment has several differences in their methodology, mentioned in Table 1 (Norris, 2001; Ord, 2008). Because of these differences, LCC and LCA will be analyzed separately in the current project, but both will be given serious weight. A combination tool will encourage decision makers to consider both environmental impacts and costs and will facilitate their process.

Table 1: Differences between LCC and LCA (Norris 2001) (Ord 2008).

Tool/Method	LCA	LCC
Purpose	Compare environmental impacts of different alternatives from a broad societal perspective	Consider cost-effectiveness of alternative investment from an economic perspective
Activities scope which are considered part of the Life Cycle	The physical life cycle of a product including whole pre-usage, use and end-of-life of processes	All processes related to direct cost and benefits during economic life time
Flows considered	Pollutants, resources, and inter-process flows of materials and energy	Direct costs and benefits come to decision maker
Units for tracking flows	Physical units such as primarily mass and energy	Monetary units
Time treatment and scope	Time is ignored, time assessment can be defined for a fixed time (e.g. 100 years)	Time is critical. Present valuing (discounting) of costs and benefits. Costs and benefits, which are beyond the scope of this project, are ignored

3. METHODOLOGY

Different LCA software tools have been developed in different regions: Gabi and SimaPro in Europe and ATHENA in the US and Canada (Hamidul Islama et al., 2014). Our database and my analysis for LCA will be obtained from Athena Sustainable Material Institute. Athena libraries were used as a Canadian database to obtain background data for various building assemblies and different building life cycle processes and activities (such as transportation and site activities, service energy and operation process, and end-of-life disposal) (Athena Sustainable Materials Institute, 2014). Also for life cycle costing, the regulations of BS 15686-5:2008 and RS Means Cost Estimate database are used.

Thirty-six wall assemblies are modulated on our case study in designbuilders software (Energy Plus). These wall assemblies are defined according to different options. These variables include; different types of wall insulation (Cellulose, Fiberglass, Polyisocyanurate (Polyiso), Extruded polystyrene (XPS) and Expanded Polystyrene (EPS)), building construction types (New Building, Renovated Building), variation in R-Value (different thickness), and different climate conditions (Vancouver, Toronto)

3.1. Reference building

Our case study is a simulated single-family house, one of which I will place in Vancouver, Canada, and the other in Toronto, Canada. This building is theoretically located in the city center.

The building is a two-storey detached house with 128m² area designed by Taylor Oppenheim Architects. As a "Green Home," it has some energy-

saving features such as double-glazing. It has brick veneer external walls with stud framed internal walls; it also has a concrete slab to the ground floor, and the roof has foil insulation.

Scenarios with low to medium WWR and fiberglass window frame result in the lowest impacts. The research accordingly shows that use phase of the life cycle is the primary contributor to most environmental impact categories for all scenarios (Rahman Azari).

3.2. Sensitivity study parameter

We model twenty wall assemblies (Theoretical study) with different insulation types and thickness in Designbuilder (Energy Plus) software with different R-Values to undertake a parametric analysis in two climate zones (Toronto, Vancouver). These theoretical wall assemblies are defined in Table 2, many of case have lower insulation thickness according to ASHRAE code.

At the end of this step, several optimization scenarios will be done to find the most environmentally friendly and cost-efficient option.

Also, sixteen scenarios (practical study) will be defined for a retrofit job as well as for new double insulation wall assemblies, which are shown in Table 3. One cellulose insulation wall will be considered according the code as the baseline. Six double-stud insulation walls are created by adding stud and by increasing interior insulation to baseline. Adding three types of insulation to the outside of the baseline wall makes nine other scenarios. This part of the study is practical part because all sixteen scenarios are designed according to ASHRAE standards.

Table 2: Theoretical wall assemblies

Cellulose	89 mm thick, 2.3 m ² K/W	Polyiso	13 mm thick, 1.0 m ² K/W	XPS	25 mm thick, 0.9 m ² K/W	Fiberglass	88 mm thick, 1.9 m ² K/W
	132 mm thick, 3.4 m ² K/W		16 mm thick, 1.0 m ² K/W		50 mm thick, 1.8 m ² K/W		150 mm thick, 3.3 m ² K/W
	165 mm thick, 3.9 m ² K/W		19 mm thick, 1.0 m ² K/W		75 mm thick, 2.64 m ² K/W		225 mm thick, 5.3 m ² K/W
	221 mm thick, 5.3 m ² K/W		25 mm thick, 1.3 m ² K/W				300 mm thick, 6.7 m ² K/W
	276 mm thick, 6.7 m ² K/W		38 mm thick, 1.9 m ² K/W				
			50 mm thick, 2.5 m ² K/W				
			75 mm thick, 3.8 m ² K/W				
			100 mm thick, 5.1 m ² K/W				

Table 3: Practical wall assemblies

Cellulose	140mm (Baseline)	Cellulose	140mm 25mm XPS
			140mm+ 50mm Xps
			140mm + 76mm Xps
	140mm +50mm		140mm 25mm EPS
	140mm + 76mm		140mm+ 50mm EPS
	140mm + 101mm		140mm + 76mm EPS
	140mm +50mm fiberglass		140mm 25mm Polyiso
	140mm + 76mm Fiberglass		140mm+ 50mm polyiso
	140mm + 101mm Fiberglass		140mm + 76mm polyiso

3.3. Optimization study parameters

Any of the scenarios do optimization between two objectives (LCC & LCA) and Thirty-six wall assemblies. The aim of these scenarios is to calculate at least LCC and LCA between all walls.

For the LCC analysis, we will use the BC Hydro database to acquire the utility price (Natural gas costs 3.82 cents per kWh and electricity cost 7.97 cents per kWh). We will also use an RS means database to calculate the construction costs for all scenarios and defined in designbuilder.

For LCA, using Athena calculates equivalent CO₂ for all types of insulation, which is as input embodied CO₂ in Designbuilder software.

LCC considers a building's economic lifetime (the time in which a building is profitable), but LCA uses the physical lifetime (the time in which building is useable physically). The point is that to use both LCC and LCA in one project and achieve a comprehensive analysis, and the lifetime should be the same.

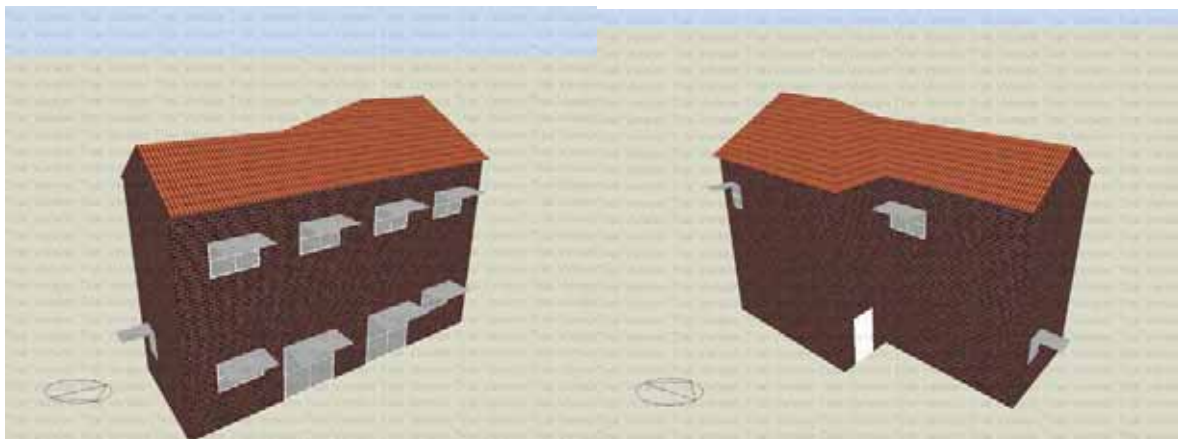


Figure 1: Simulated house in Designbuilder software

Figure 4: Total Energy Consumption

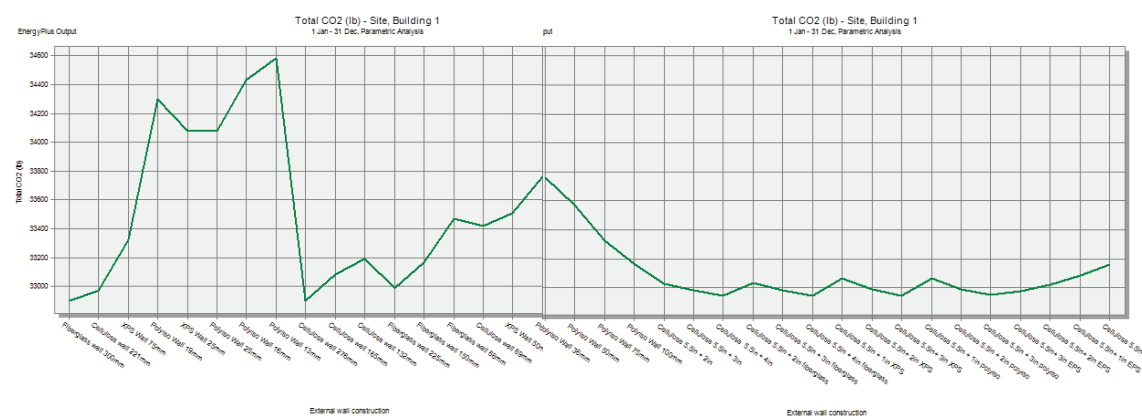


Figure 5: Total CO2

Toronto Climate

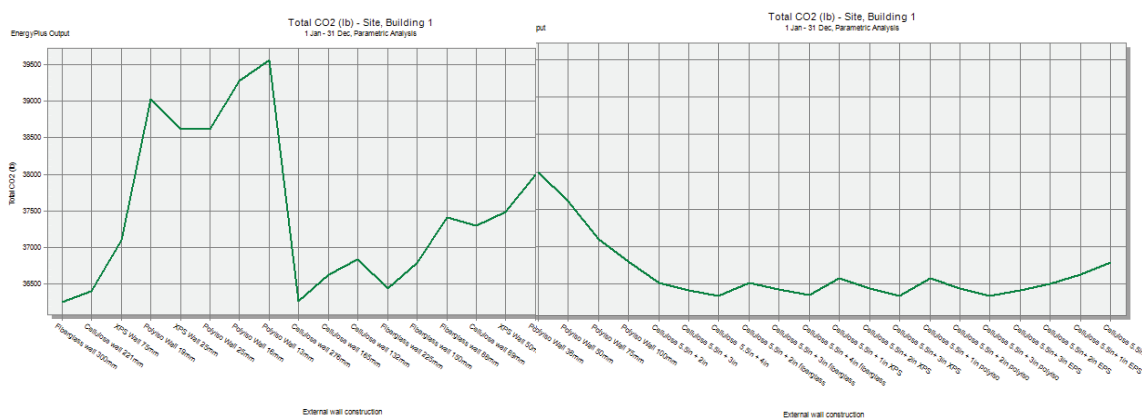


Figure 6: Total CO2

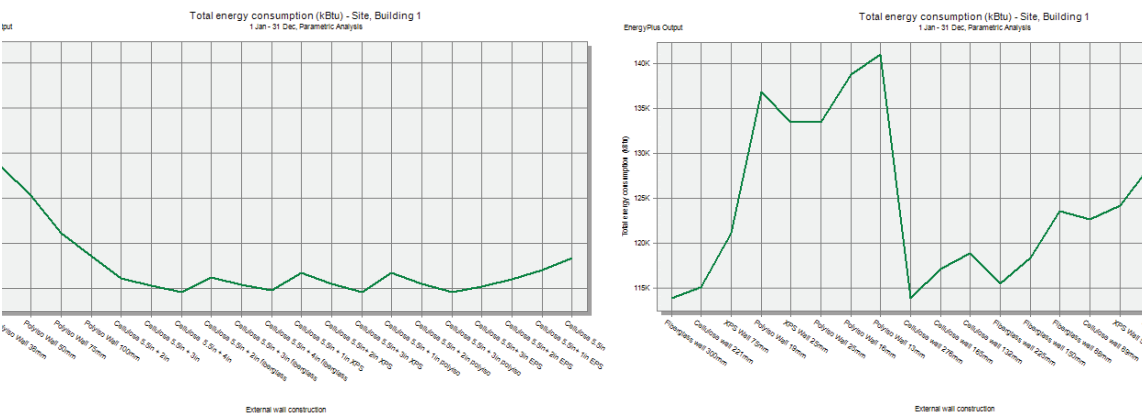


Figure 7: Total Energy Consumption

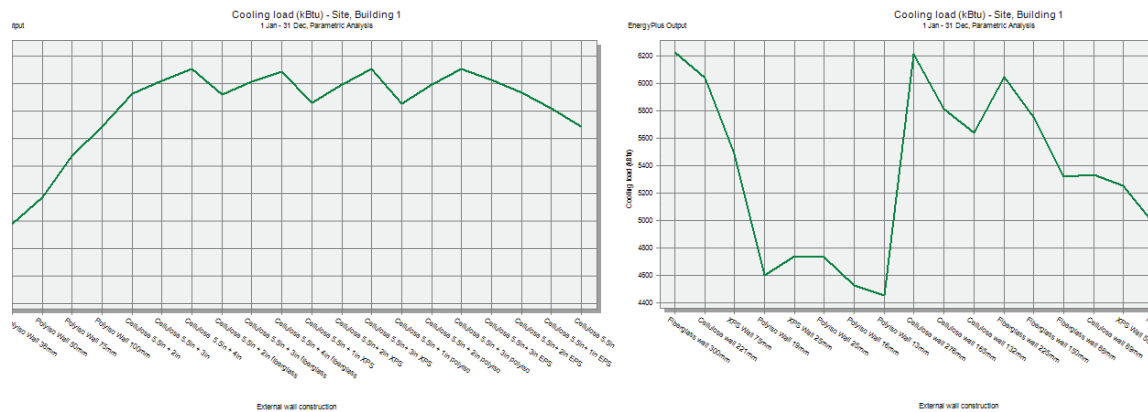


Figure 8: Cooling Load

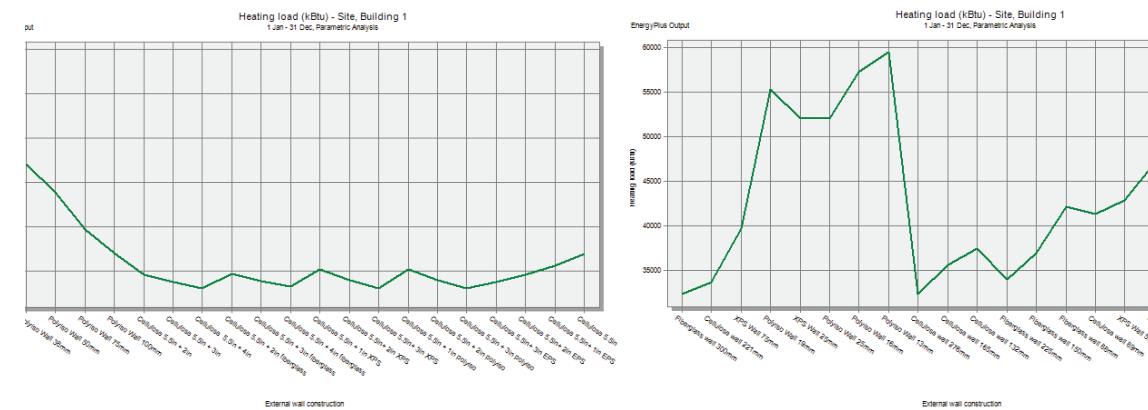


Figure 9: Heating Load

4.2. Optimization analysis

In this part, all theoretical and practical wall assemblies are modeled, and thirty-six scenarios are compared together. Lifecycle Cost and Life Cycle Assessment (life cycle CO₂) optimization analysis is a comprehensive analytical method for selecting the most sustainable wall assembly options.

Cellulose 89mm is one of optimal design with lowest LCC and average LCA for the two climates. But Cellulose 132mm, fiberglass 150mm, and Cellulose 5.5in + 1 XPS are other good practical option for both climates which are shown in figure 10 and 11.

Cellulose 5.5in + EPS insulation also are other appropriate options. In additional fiberglass with 225mm or 300mm have low LCA effect, but they have a higher price. And also Polyiso with low thickness (13mm, 16mm, 19mm) are the worst option, and they have highest LCA.

In Vancouver

By increasing cellulose thickness from 89mm to 276mm, LCA 6.28% and LCC 2.1% will be increased. Cellulose 132mm is minimum acceptable insulation thickness according to ASHRAE, By increasing cellulose thickness from 89mm to 132mm; LCC will increase 1.23%, and LCA will increase 2.38% because of increasing the embodied energy. These result shows, the embody energy and also embody CO₂ of insulation has a great effect of their LCA in mild climate look like Vancouver. But the operational energy has more force in a harsh climate like Toronto than in mild climate such as Vancouver.

And also if a building has less opening and less air leakage, it can have less operational energy and also less LCA and then for this kind of building embody the energy of the material can be dominated effect

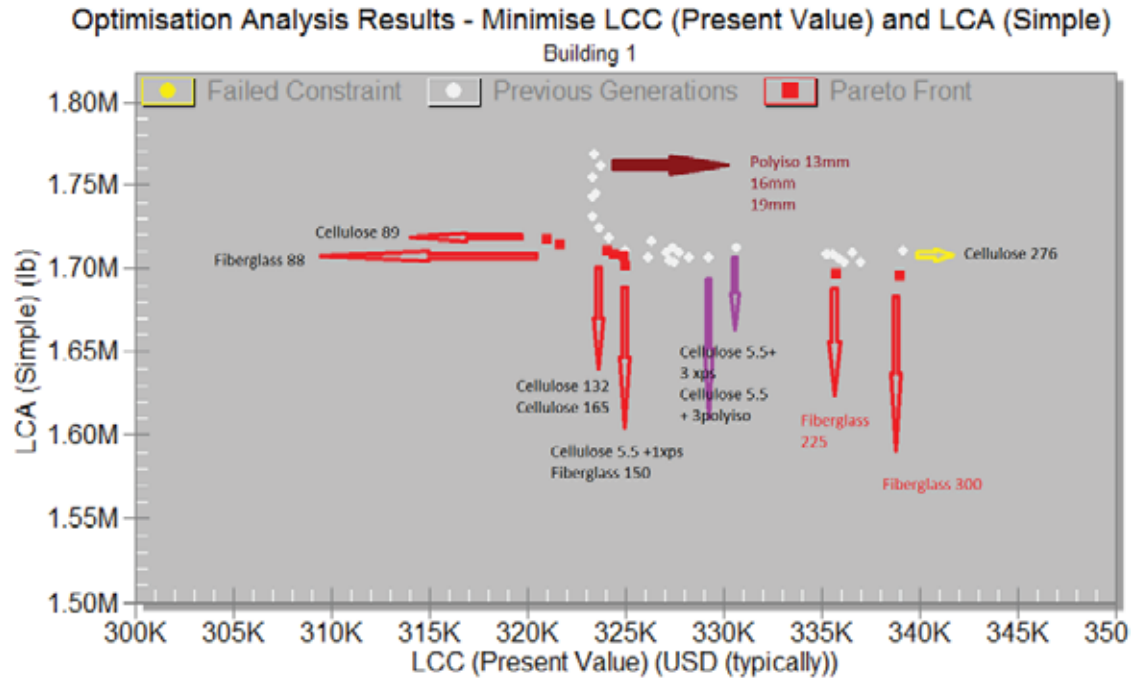


Figure 10: Optimisation Analysis in Vancouver Climate

In Toronto

Cellulose 132mm, Fiberglass 150mm, and polyiso 75mm are the best option base on ASHRAE standard

in Toronto climate, which are illustrated in, figure 11. Polyiso 75mm is the expensive one and also less LCA option, but cellulose 132mm is cheapest one but highest LCA option.

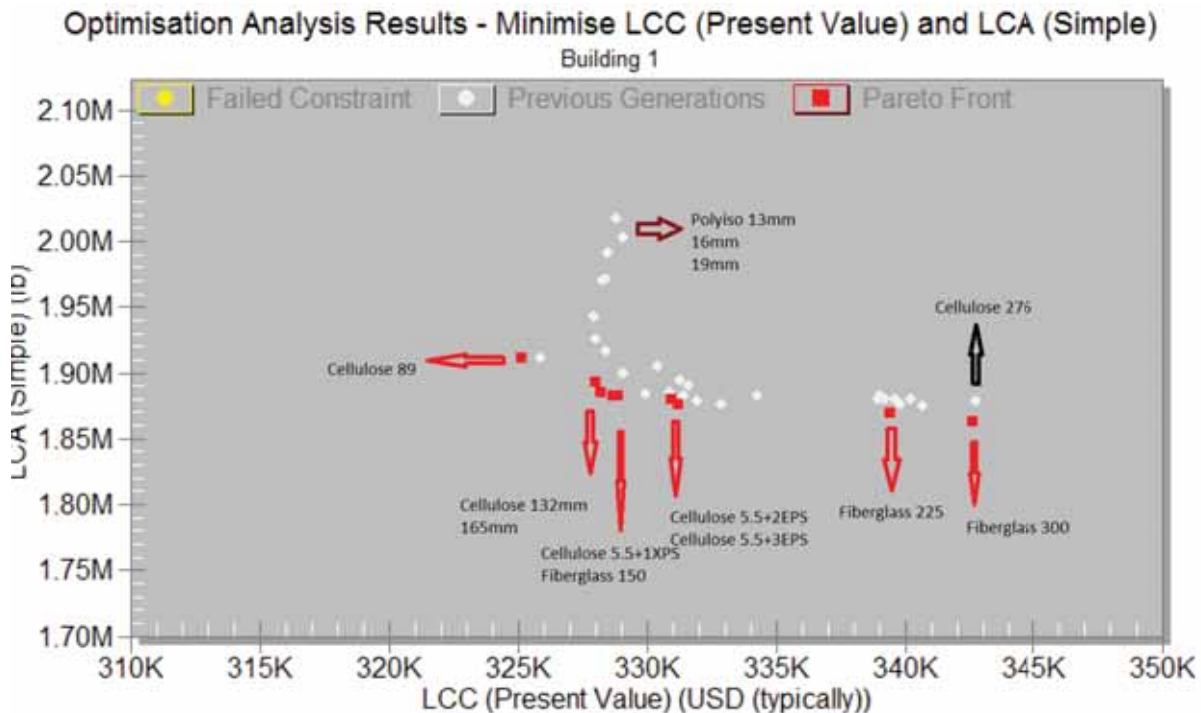


Figure 11: Optimisation Analysis in Toronto Climate

5. CONCLUSION

First of all the results show that analyzing the lifetime is critical for this analysis and also operation energy and as a result, life cycle energy is dominated in this analysis. In general, the embodied energy of wall assembly in Vancouver is more than Toronto, but the operational energy in Toronto is more than Vancouver. As a result, the embodied/ life cycle energy ratio in Vancouver is greater than in Toronto.

Minimum LCC & LCA scenario is one of the most important optimization analyses for decision-makers to assist them in designing sustainable wall assembly. Results from this study show that wall assembly with cellulose 89mm thickness is the best for both climates.

In general applying cellulose 5.5in insulation with exterior insulation is more efficient than using with additional interior insulation for both climate zones. The exterior insulation can reduce the effects of the thermal bridge so applying exterior XPS and Polyiso can reduce operational energy and then reduce operational CO₂ and also LCA. Exterior insulation retrofits which lead to a significant reduction in environmental impact, is cheaper than interior insulation retrofit in the life cycle of the building. Additional XPS or EPS are more effective than applying additional polyiso. Cellulose 5.5in + 1in (165mm) XPS, Cellulose 5.5in + 2in (190mm) EPS and Cellulose 5.5in + 3in (215mm) EPS are almost the best optimal practical designs. Using additional 4in fiberglass is the best option if interior retrofit should be applied to the case study.

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What is Sustainable Infrastructure? A review of sustainable infrastructure rating systems

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Abstract:

Infrastructure projects, have outsized impacts on the economy and sustainability of our society. They affect how people move, live and work, consumption patterns, and are a strong factor in land designation. International and federal, provincial and local policies are pushing for increased focus on sustainability society-wide including major changes in how civil infrastructure is conceived of, designed, built and maintained. Sustainable infrastructure has many facets. Critical questions remain around what is sustainable infrastructure? And how do we measure it? And what counts as sustainable? Infrastructure rating sustainability systems aim to do for infrastructure what BREEAM and LEED have done for buildings; create a standard framework and brand for sustainability. However, as the basic building block upon which civil society is based, the sustainability impacts of civil infrastructure are far reaching and in some ways more complex to capture than those of buildings, for instance a large horizontal infrastructure project can extend for kilometers, covering orders of magnitude more land than even a large building. This paper examines the credits and points awarded in five prominent infrastructure sustainability rating systems, CEEQUAL v4.1 for Projects, Envision v3, Greenroads v2, BCA Green Mark for Infrastructure v1.0, and Infrastructure Sustainability (IS) Rating Tool v1.2. The paper examines the degree of emphasis on different elements of triple bottom line sustainability (economic, social and environmental impacts). Environmental credits are further examined to assess the relative emphasis on different types of environmental impacts (e.g. air quality, GHG emissions, species protection).

Keywords:

Sustainability, Infrastructure, Rating systems.

1. Introduction

From 2016 to 2040 more than 90 trillion dollars (USD) needs to be invested in global infrastructure (energy, telecommunications, transport, water) [1]. For the world to meet stated sustainability goals such as keeping global temperature rise to below 2°C as agreed in the 2015 Paris Climate agreement or to achieve the UN Sustainable Development Goals, infrastructure must be built with purposeful and aggressive sustainability targets.

However, the concept of sustainable infrastructure is relatively new and efforts to achieve sustainability in the infrastructure sector newer still. Within the built environment sector emphasis on sustainability has to date focused on buildings (vertical infrastructure). Only more recently have efforts extended to horizontal infrastructure like energy distribution, transportation and water infrastructure. In this paper, the term infrastructure is used to refer to horizontal infrastructure unless notes otherwise. The lag between the emergence of building and infrastructure rating systems highlight the belated attention to horizontal infrastructure sustainability. The Building Research Establishment Environmental Assessment Method (BREEAM), the first sustainable buildings rating system was first released in 1990 [2]. CEEQUAL, the earliest sustainable infrastructure rating system, was released 13 years later in 2003 [3].

Just as Leadership in Environmental and Energy Design (LEED) and BREEAM certification became synonymous with “sustainable buildings” in North American and Europe, respectively, sustainable infrastructure rating systems have the potential to become arbiters of “sustainability” for infrastructure. Each rating system evaluates sustainability differently, with different emphasis between economic, social and environmental factors. Further, within environmental sustainability, the focus of credits and points vary between the rating systems; for example, one rating system rewards greenhouse gas reduction more, the other species diversity preservation. As infrastructure sustainability rating systems become more prominent it will be increasingly important to understand how they vary and how they define sustainability through the practice of awarded points and certification. This paper examines five prominent sustainable infrastructure rating systems to evaluate what approach and values are rewarded with credits and certification, thereby subtly defining what it means to build sustainable infrastructure.

The structure of this paper is as follows. Section 2 provides context for this research. Section 3 summarizes the studied rating systems. Section 4 lays out the methods used to categorize points and credits from each rating system. Section 5 presents the results of the categorization. The paper concludes with a discussion of the findings in section 6.

2. Background

Sustainability is a somewhat amorphous term meaning different things to different people; many have put forward definitions. The most well known comes from Brundtland in 1987, "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs." [4]. The Brundtland report "Our Common Future" was specifically focused on addressing environmental concerns; accordingly, its definition of sustainability has a strong environmental bent. Environmental concerns remain the foundation of sustainability through many different proposed definitions [5].

In 1994, Elkington proposed a "Win-Win-Win for businesses" that set the framework for the triple bottom line (TBL) sustainability framework he further detailed in 1997's "Cannibal with Forks". TBL sustainability requires equal footing for economic, social and environmental considerations [6], [7]. Elkington's work was founded on the realization that social and economic dimensions of the sustainability discussion needed more prominence for real world environmental progress to take place [8].

Societal scale sustainability will not be possible without widespread changes in the infrastructure sector. The economic, social and environmental impacts of infrastructure are massive. The types, quality and quantity of infrastructure influence prosperity, income inequality, productivity and social well-being [9]. In Canada alone, infrastructure construction (horizontal and vertical) contributes \$171 billion to GDP while accounting for 40% of national energy use and 50% of primary materials consumption [10]. Adoption of TBL sustainability in the infrastructure sector has been slow; economic considerations continue to dominate. As Whitehead (2015) describes, Balfour Beatty, the international construction services firm, produced its first sustainability report in 2003, only 10 years later after a change in leadership, did sustainability become a key part of how the company manages projects [11]. The construction sector is traditionally fragmented and slow to change [12]; this can hamper adoption of sustainable practices, like the adoption of new environmentally sustainable building materials [13]. A central challenge to the adoption of sustainability in the infrastructure sector is the need for effective frameworks for analysing the long-term impacts of projects [14]. Sustainability infrastructure ratings systems are one solution for providing standard evaluation frameworks and encouraging faster adoption of sustainable practices in the infrastructure sector. Another key challenge to understanding the full sustainability impacts of infrastructure projects lie in the numerous knock on impacts infrastructure. A rail project, for instance, has environmental impacts associated with construction, operation, travel,

behaviour, and land use [15]. Much of which is hard to measure prospectively.

The TBL approach to sustainability has become widely accepted. It is also criticised for the difficulty of its application in practice. A key criticism is that TBL sustainability does not provide a framework for prioritizing the needs of different stakeholders or between different aspects of sustainability [16]. There is a tension between the three bottom lines; which should be optimized for? Is a project sustainable if it achieves just two of the three goals? (e.g. economically and socially sustainable but not environmentally?). Further, each category is very broad, especially social and environmental sustainability. Social sustainability includes, education and training, inter and intra-generational social justice, health, safety, fair distribution of income, employment, cultural traditions, social interaction, social networks and more [17]. Environmental sustainability includes, construction waste, energy use, land use, water use, contaminants, chemical use, air pollution, GHG emissions and more [14]. Again questions arise as to how many aspects of each category need to be addressed to be sustainable and which are the most important? According to the Nature Conservancy, the number one environmental challenge facing humanity is the need to reduce greenhouse gas emissions [18]. Which raises the question, should aggressive reduction in GHGs be a prerequisite to the sustainability label?

Sustainability assessments facilitate identifying, predicting and measuring the TBL impacts of human activities [19]. As interest in sustainability in the built environment grew in the 1990s and 2000 third party certifiers of projects arose and gained in popularity. By the end of 2017 BREEAM had issued 563,271 building certifications in 77 countries [2]. A further 109,974 are certified by LEED [20]. In the last decade, more attention has been given to infrastructure; it is reasonable to predict that in the next decade infrastructure rating systems will see increased prominence. CEEQUAL, the oldest of the infrastructure rating systems has now certified more than 360 projects worth more than CAD \$50 billion [21].

3. Sustainable Infrastructure Rating Systems

The five rating systems that were studied are CEEQUAL v4.1 for Projects, Envision v3, Greenroads v2, BCA Green Mark for Infrastructure v1.0, and Infrastructure Sustainability (IS) Rating Tool v1.2. Selection was based on prevalence in the industry, availability, and geographical diversity. Table 1 provides an overview of the rating systems. A brief summary of each rating system is provided below. All of the rating systems operate on a credit and points system, with a maximum number of points per credit. The ratings systems include both mandatory and optional credits. With the exception of Greenroads

mandatory credits which must be achieved as a prerequisite to certification the paths to collect points are at the determination of the projects.

Improving sustainability awareness and adoption of sustainable practices are common objectives across the rating systems. Towards these common goals, each rating system takes a different approach to sustainability and prioritizes different benefits. The rating systems present two main approaches to sustainability: a decision support tool or a prescriptive set of measures to be implemented. CEEQUAL states its evidence-based criteria differentiate it from decision-support tools [22], while Envision promotes that its decision-making framework is more flexible than prescriptive measures [23]. The rating systems also vary in term of the stage of projects they assess. Envision and Greenroads only certify complete projects, while CEEQUAL and IS also certify projects at the design stage. CEEQUAL certifies only the construction phase of a project, while IS assessment can include operation of the infrastructure.

The promoted benefits of each rating system are similar, but are not necessarily presented with equal importance. While non-environmental benefits, such as cost savings and positive public image, are promoted across the rating systems, these are more prominently marketed in CEEQUAL than IS, for example. CEEQUAL highlights the adoption of construction best practices, reputation and cost savings [22], while IS highlights consistent sustainability definitions, assessments, and the incorporation of life cycle considerations [24].

All the rating systems acknowledge that there are more points available than any given project could achieve. A diversity of optional credits and points are provided to suit the different needs and priorities of different projects. Top level certification requires achieving between 50% (Envision) and 75% (CEEQUAL and IS) of the total available points.

3.1 CEEQUAL

CEEQUAL was originally developed by the Institution of Civil Engineers (ICE) in the United Kingdom. The first version of CEEQUAL was released in 2003 [3]. CEEQUAL v4.1 was released in August 2010 and focuses on environmental sustainability [25]. The newest version, CEEQUAL v5.2, has expanded to include triple bottom line sustainability [22], but is only available to accredited CEEQUAL Assessors, and was not available for this research.

CEEQUAL mandatory credits must be assessed, but must not all be satisfied for certification. For example, CEEQUAL credit 1.1.1 requires the project to report if a documented commitment to environmental aspects at all stages was adopted. A answer of no results 0 points but does not disqualify the project from CEEQUAL certification.

3.2 Envision

Envision, originally released in 2012 and currently undergoing an update, is a joint endeavor of the Infrastructure Sustainability Institute (ISI) and the Zofnass Program for Sustainable Infrastructure at Harvard University [26]. ISI is based in Washington, D.C., USA, and was founded by the American Public Works Association (APWA), the American Society of Civil Engineers (ASCE), and the American Council of Engineering Companies (ACEC) [27]. The version used in this study is a draft version 3 that was released in September 2017 for public comment.

3.3 Greenroads

Originating from the University of Washington in 2011, Greenroads is currently maintained by Greenroads International, and was most recently updated in September 2017 [9] [10].

Greenroads requires assessment, and satisfactory completion, of 12 mandatory credits as a prerequisite to certification. These credits include the requirement for full life cycling costs of the project, calculation of embodied greenhouse gas emissions from construction, a utility conflict analysis and community engagement. For 38% of the optional credits, there is more than one pathway to achieve points, such as in EW-6 where points can be achieved for balancing earthworks or by remediating contaminated soil on-site.

3.4 BCA Green Mark

BCA Green Mark, created by the Building and Construction Authority (BCA), originated as a green building rating system in Singapore in 2005, and has since broadened its scope and introduced the infrastructure scheme in 2009. Minor updates were made to the version used in this study in January 2017. Only the credit descriptions for BCA Green Mark were available for this research; more data on the certification process would be valuable.

3.5 IS Rating Tool

The Infrastructure Sustainability Council of Australia (ISCA) released the first Infrastructure Sustainability (IS) rating tool in 2012 with the most recent update in June 2017.

Credits in IS are given either a constant or alterable weight based on project details, and the total points are normalized to a 100-point scale

Table 1 Summary of rating systems

Category	CEEQUAL	Envision	Greenroads	BCA Green Mark	IS Rating Tool
Version	4.1 for Projects	3 (DRAFT)	2	1.0 for Infrastructure	1.2
Release Date	August 2010	September 2017	September 2017	January 2017	June 2017
Authority	ICE - Institution of Civil Engineers (Originator) BRE Group (Current) [22]	ISI - Institute for Sustainable Infrastructure and Zofnass Program (Harvard)	University of Washington (Originator) Greenroads International (Current)	BCA - Building and Construction Authority	ISCA - Infrastructure Sustainability Council of Australia
Scope	Civil engineering infrastructure, landscaping, and public space works	Civil engineering infrastructure	Most transportation-related infrastructure (roads, bridges, transit-related)	Transportation-related infrastructure and some utility (e.g. hydropower dams)	Transportation infrastructure, water and utility transmission, public space works, and civic buildings.
Location Applicability	UK and Ireland, International [†]	US and Canada, International	International	Singapore	Australia and New Zealand
Sustainability	Environmental	Triple Bottom Line	Triple Bottom Line	Environmental	Triple Bottom Line
Stage of Assessment	Dependent on award type; design-only and as-built	As-built certification	As-built certification	Details Unavailable	Dependent on award type: design-only, as-built, and operational assessment
Type of rating system	Credit and points based 226 credits and 2004 points Mandatory and optional credits	Credit and points based 64 credits and 1049 points Optional credits only	Credit and points based 61 credits and 130 points Mandatory credits (worth 0 points) and optional	Credit and points based 26 credits and 130 points Optional credits only	Credit and points based 44 credits and 110 points normalized to a 100-point scale Alterable credit weightings
Levels of Certification*	Excellent: 75% Very Good: 60% Good: 40% Pass: 25% [30]	Platinum: 50% Gold: 40% Silver: 30% Bronze: 20% [31]	Evergreen: 61% Gold: 46% Silver: 38% Bronze: 31% + all Mandatory credits [29]	Platinum: 69% Gold Plus: 61% Gold: 54% Certified: 38% [32]	Leading: 75% Excellent: 50% Commended: 25% [33]
Process of Certification	- Trained assessor involvement required - Self-assessment - Verification	- Envision specialist involvement is required - Self-assessment - Verification - Authentication	- Pilot project assessment (optional) - Documents submission - Greenroads assessment - Board of Directors sign off on certification	Details Unavailable	- Self-assessment - Verification - Certification
Projects Certified**	360 certified projects CAD \$51 B [21]	39 certified projects [34]	131 certified projects [35] CAD\$12.7 B [29]	Details Unavailable	20 certified projects CAD\$7.7 B [36]

[†] CEEQUAL international adaptations can be made by completing a credit-weighting exercise with CEEQUAL [37]

*For levels of certification that were provided in number of points, percentage of total possible points was calculated

**Values of certified projects converted to CAD on Nov. 27, 2017

4. Methods

A two-step categorization approach was used to analyze the five rating systems. In the first step (A), each credit and its respective points are assigned a bucket related to triple bottom line sustainability. Second (B), the environmental credits are examined in more detail to investigate which types of environmental measures are emphasized. The goal of the analysis is to investigate what sustainability interventions are rewarded by the rating systems and to what degree.

A. Each rating system was reviewed credit by credit. Every credit and the associated maximum number of points were counted towards 1, or more, of 5 buckets: Environmental, Economic, Social, Project Management, and Innovation. The definitions used for categorization are listed in Table 2. The breakdown of points available in each bucket category is illustrated in Figure 1. Credits that strongly fit into more than 1 bucket were assigned to all the applicable buckets to a maximum of 3. These co-categorized credits account for 16.6% of all credits. Project Management was included as a category to capture credits which are primarily motivated by project management best practices. For example, CA-8: Procurement Integrity in Greenroads encourages transparent, ethical, and fair contracting methods through internal ethics reviews and establishment of a whistleblower hotline. Similarly, Innovation was included to represent the points awarded for innovative measures or performance above the highest level. For example, the IS credit Inn-1 awards 5 points for a world-first innovation, 3 for an Australia-first, and 1 for an innovative technique that has been used in another Australian project.

Greenroads mandatory credits, which are not worth points, were categorized independently from the optional credits, and the distribution was based on the number of credits instead of the number of points.

The percentage of credits that fit strongly in 2 buckets was 14.0%. To illustrate how these credits and points affect the distribution, overlapping areas are shown in Figure 1 (e.g. Project Management and Environment, Social and Environmental). An example of such a credit is 5.1 in BCA Green Mark which considers how prefabricated elements can ease construction, reduce water usage on-site and waste generation. These meets both project management (ease construction) and environmental (energy and water) aims and was assigned to the overlapping Project Management/Environmental bucket.

The IS rating system includes a number of credits that fit into more than two buckets, these represent 2.6% of all credits across the 5 rating systems. In these credits base points are awarded for an environmental consideration, but maximum points relied on the extension of the approach to include economic and social factors. For example, IS Man-4- Inspection and Auditing awards the first level achievement for completing environmental audits during construction, and the second level of achievement requires sustainability audits that take into consideration economic and social factors. For visual clarity, these credits were split into the three buckets in Figure 1; 60% of points in the Environmental bucket and 20% of points in both Social and Economic buckets.

Table 2 Step A: bucket categorizations

Level A Bucket	Description	Example
Environment	Reduction in environmental impacts and restoration of environment where possible	Greenroads EW-2: Ecological Connectivity, reduce fragmentation and improve biodiversity
Economic	Consideration of life cycle economic impacts, or economic stimulation	Greenroads PR-6: Lifecycle Cost Analysis, includes capital, operational, and maintenance costs
Social	Meaningful stakeholder engagement and community participation, improved accessibility	BCA Green Mark credit 1.7, increasing public amenities and improved accessibility
Project Management	Incorporation of construction best practices, improved resiliency, deconstruction plans at end of the useful life	CEEQUAL credit 2.3.1, completion of flood risk assessment for the useful life of the project
Innovation	Atypical measures that promote sustainability, but are not within the rating system's current scope of assessment, or exceeding expectations	Envision QL 0.0: Innovate or Exceed Credit Requirements, beyond the expectations of the rating system
Environment and Social	Beneficial impacts to both social and environmental communities, such as air quality and multimodal connectivity	IS Dis-4: Air Quality, improved air quality benefits both local ecology and human communities
Social and Project Management	Construction practices that benefit the community, such as Health and Safety programs	Envision QL1.2: Enhance Public Health and Safety, both on the project site and in the broader community
Social and Economic	Economic benefits focused on local community, equitable wages for workers	CEEQUAL credit 5.3.10, promotion of heritage conservation skills and support for heritage employment
Project Management and Environmental	Dually motivated by the environment and the benefits to the project, such as waste management plans	CEEQUAL credit 9.4.1, identifying waste streams in the project with a goal of recycling and reuse

B. For the second step, environmental credits and respective points, including those categorized in dual buckets, were further categorized into 1 or more of 9 environmental buckets: 1) Greenhouse gas (GHG) Emissions, 2) Energy, 3) Air, 4) Water, 5) Land, 6) Species, 7) Materials, 8) Commitment, and 9) Credentials. The definitions used for categorization are listed in Table 3. The breakdown between these buckets is illustrated in Figure 2. The first seven buckets were chosen for their prevalence across all five rating systems. While GHG Emissions deals strictly with the reduction of GHG emissions, and Air with air quality, the others encompass a number of strategies. Energy includes energy efficiency, absolute reduction in energy needs, and the use of renewable energy, while Water includes reduction of water usage in construction and operation, as well as water pollution prevention. The Land bucket covers the preservation of prime farmland and the remediation of contaminated soil, while Species includes the connectivity of habitats, and controlling invasive species. Materials includes the reduction of material

usage and landfill diversion, as well as the use of recycled materials. The Commitment bucket captures credits with broad environmental motivations, such as BCA Green Mark credit 4.2 Environmental Management System that requires the development and implementation of environmental policy and programs. The Credentials bucket captures credits that are based on qualifications, for example CE-1 Educated Team in Greenroads that requires at least one team member is a trained Sustainable Transportation Professional.

Credits that fit strongly in 2 or more environmental buckets represented 16.5% of all the environmental credits. In figure 2 these points are divided into the relevant buckets. For example, the IS credit Eco-1 promotes preserving the ecological value of the land, which was categorized as both Species and Land. For Figure 2 the 7.5 points for Eco-1 were split in half and counted towards the Species and Land buckets. The percentage of environmental credits that fit strongly in 2 buckets was 15.1% and 1.4% of credits fit into more than 2 buckets across the 5 rating systems.

Table 3 Step B: Environmental bucket categorizations

Level B Bucket	Description
GHG Emissions	Reduced GHG emissions in construction and/or operations
Energy	Reduced energy use for construction and/or operations, use of energy efficient technology, renewable energy
Air	Reduced air pollutants in construction and/or operations
Water	Reduced water usage for construction and/or operations, use of grey water or water efficient technology, reduced runoff, improved runoff quality
Land	Avoided impact on sensitive ecological areas, including farmland, remediate contaminated soil, prevent contamination, protect pre-development ecology, reuse of soils
Species	Avoided impact on sensitive ecological areas, preferred use and protection of native species, habitat conservation, increased biodiversity, reduced light and noise pollution
Materials	Reuse of materials, use of recycled materials, waste management at both construction, operations, and end of useful life
Commitment	General environment-focused measures; not clearly linked to specific environmental goals, such as environmental policies and programs
Credentials	Team member(s) or contractor(s) hold specified qualifications related to sustainability practices

5. Findings

All the rating systems, those explicitly focusing on environmental sustainability and those claiming TBL sustainability, allocated more than 50% of points to Environment (excluding co-categorized credits/points) (prerequisite mandatory Greenroads credits do not awards points).

CEEQUAL and BCA Green Mark, which explicitly target environmental impacts, reflect that priority in their credits with Environment accounting for 60% of the points. For CEEQUAL including co-categorized points (e.g. Environment-Social) this percentage rises to over 70%. However, the rating systems pursuing TBL sustainability emphasizes the environment only somewhat less. The Social bucket was generally the next largest portion of each rating system, ranging from 10.8% in BCA Green Mark to 22.1% in IS (again, (excluding co-categorized credits/points). Project Management points account for around 10% of points for 3 out of 5 rating systems. The exceptions are BCA Green Mark which has no Project Management points, and Envision where project management accounts for 19% of total points. Innovation points factor quite differently across the rating systems; no innovation points are available in CEEQUAL, and almost a quarter of BCA Green Mark points are for innovation. Economic points were much less prominent, ranging from 0.0% in BCA Green Mark to 8.3% in Greenroads mandatory credits.

The lack of Economic emphasis is particularly notable across the ratings systems. However, this should be considered in context, the conventional method of project management requires intense focus on the economic viability of a project, the rating systems can be excused for not further focusing on economic

sustainability. Additionally, economic impacts will stem from some credits classified in other buckets. Project Management credits, that were counted separately from Economic credits, may have economic motivations. For example CEEQUAL credit 8.7.1, classified into the Project Management bucket, requires consideration of the durability of the project and future maintenance needs, could influence long term maintenance costs. Similarly, many Environmentally motivated credits could have dual benefits, such as cost savings associated with reduction in material use and waste. BCA Green Mark credit 5.2 requires efforts to balance onsite earthworks to minimum soil taken offsite; this could have the co-benefit of reducing dumping fees.

While social credits made up a significant percentage of overall points, many of these were focus on minimizing the impact of construction on neighbours (e.g. noise, dust, traffic minimization), a worthy goal but not central to many definitions of social sustainability (e.g. income inequality). Other social concerns included consideration of historical preservation, work site safety, and consultation processes with local groups. Very few credits were targeted at social equity (e.g. racial disparity, poverty reduction, meeting needs of underserved communities). A few exceptions are, Credit 12.2.3 in CEEQUAL which promotes the development of relationships with local groups through the donation of skills or surplus materials, Envision LD3.2 which gives points for establishing training programs for the local workforce. Greenroads CA-11 Path 1 requires that 25% of project funds are dedicated to certified small businesses or female-owned businesses.

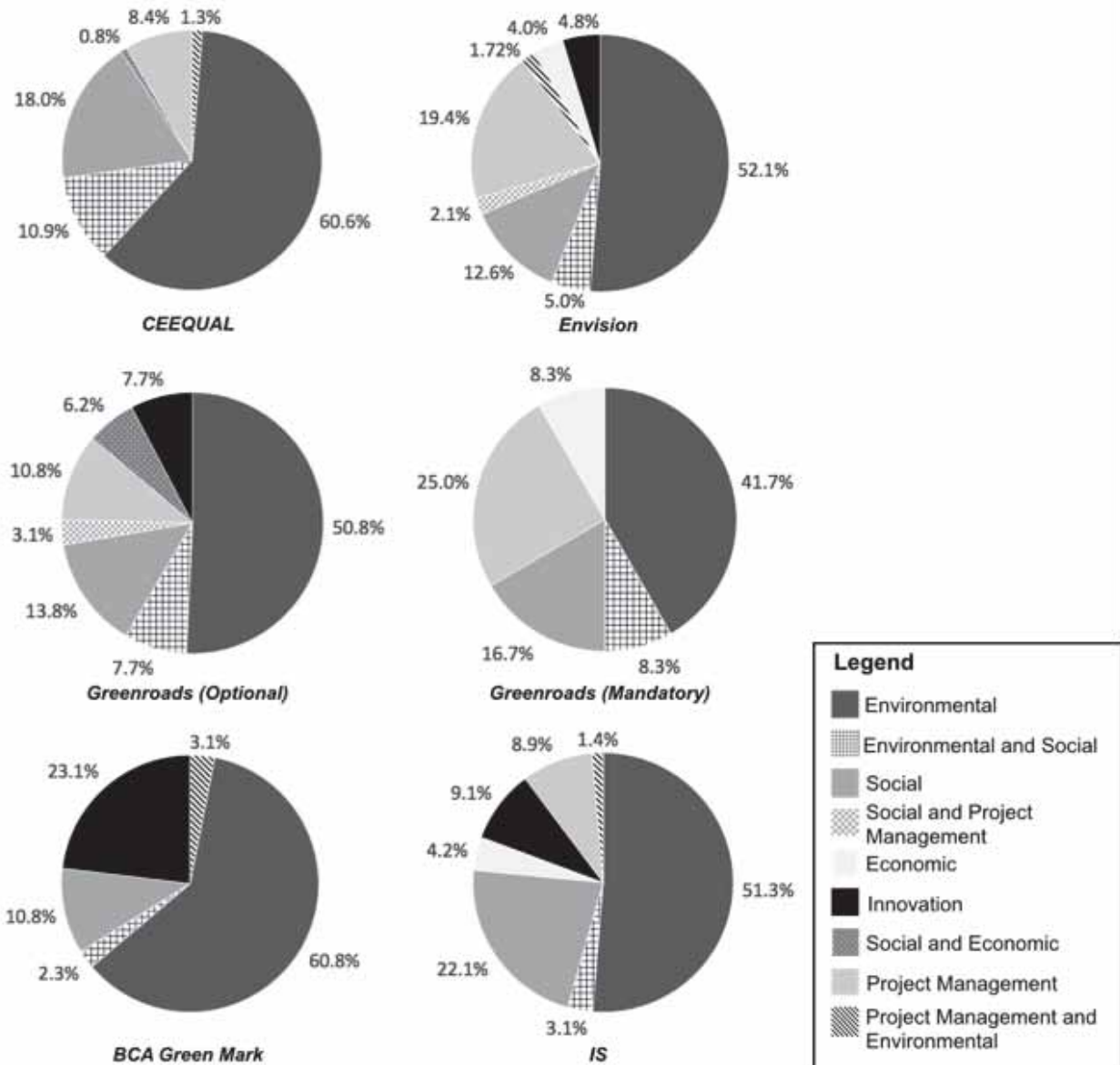


Figure 1 Breakdown of rating system points between Economic, Social, Environmental, Project Management and Innovation impacts

As the main focus of all the rating systems environmental sustainability was analyzed in more detail. The five rating systems allocated points to each of the 9 considered environmental factors. While the emphasis varied between the rating systems, all are taking a broad approach to incentivising improved environmental impacts of infrastructure – from water quality to reductions in GHG emissions. Most of the environmental credits require concrete changes that will improve some aspect of environmental sustainability. For example, IS credit MAT-1 requires life cycle assessment of material use and a marked reduction in consumed materials. The Commitment and Credential points, which most notably account for >10% in both CEEQUAL and Envision, do not have a direct impact on environmental sustainability. Envision credit LD1.1 Provide Effective Leadership and Commitment measures the projects official sustainability commitments and policies.

As illustrated in Figure 2, the most important aspect of environmental sustainability varied between rating systems. In Envision, 14.1% of environmental credits are for land impacts, 29.1% energy in BCA Green

Mark, 19.9% for materials in CEEQUAL, 17.7% for water impacts in IS, 19.7% for GHG emissions in Greenroads. Relatively few points were dedicated to air quality impacts across the rating systems (0.66% in Greenroads to a maximum of 6.0% in CEEQUAL). Commitment credits were weighted very differently across rating systems, with Greenroads having 0.0%, and both CEEQUAL and Envision having approximately 7%. Water accounted for between 9.6% of environmental points in CEEQUAL, up to 13.3% in BCA Green Mark. GHG Emissions also figured prominently in the 5 rating systems, accounting for around 10% in each rating system, with the exception of BCA Greenmark at 6.2%.

The vast majority of credits across all rating systems focused on the construction phase of the projects and required detailed data on how the project was delivered. As such the rating systems are limited in their ability to prospectively evaluate the sustainability of a proposed projects or for comparison between competing proposal. The rating system are also no structure to capture the knock-on impacts inherent to many, particularly transport, infrastructure projects.

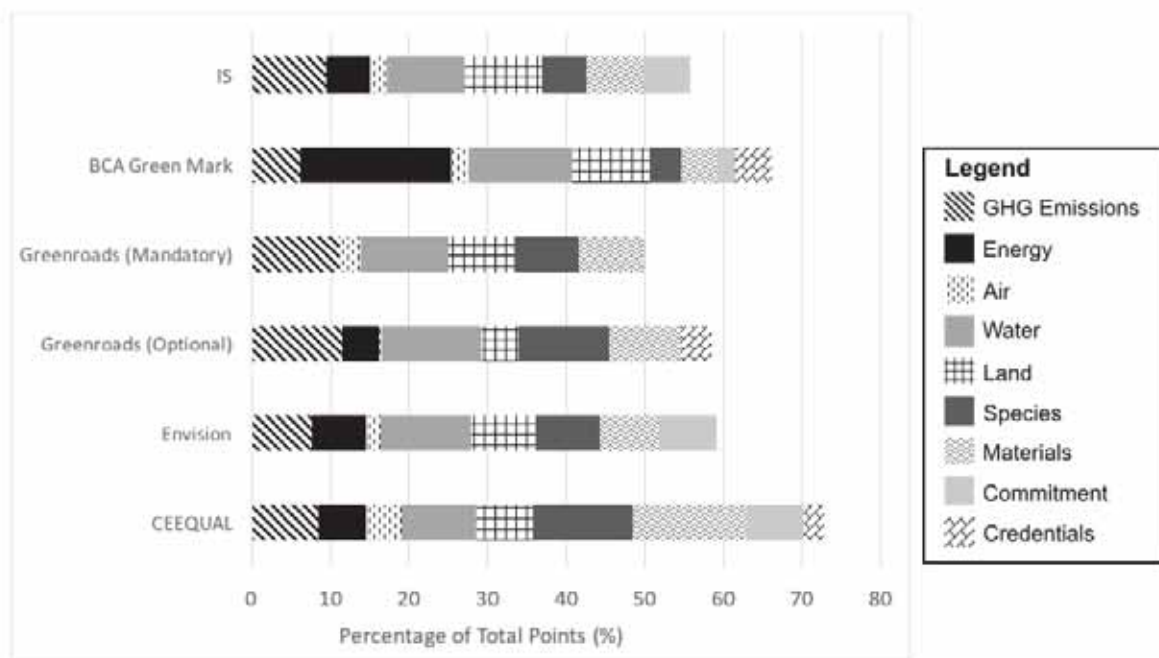


Figure 2: Level B - Environmental Bucket Analysis (including environmental credits co-categorized with social, economic, project management and or innovation credits)

6. Discussions and Conclusions

The diversity of credits and points in each rating system means they are broad and applicable to a wide range of projects and situations. The amount of points dedicated to each aspect of TBL sustainability is worth considering in light of the certification thresholds of each rating system. For the highest level of certification, 50% (Envision) to 75% (CEEQUAL and IS) of available points are needed. For 3/5 rating systems this would require achieving points in at least 2 buckets with a high number of Environmental credits needed at a minimum. In Envision, top level certification could be achieved by getting nearly all of the environmental points. Greenroads avoids the risk of projects with all points concentrated in only one category through the use of prerequisite credits which are distributed across TBL sustainability and project management. Given that environmental motivations were the genesis of sustainability the potential to achieve a “sustainability” certification based predominantly on environmental credits may not be objectionable, but it is at odds with the goals of rating systems that define themselves as TBL (Envision, Greenroads, IS).

At the lowest end of certification, 20% Envision to 38% for BCA Green Mark, certification, in theory, can be achieved without, for instance, any environmental credits. For example, the Project Management points in Envision account for 19% of points; 1% shy of the 20% requirement. Investigation the implications of this in practice is outside the scope of this paper and would be an interesting avenue for future research.

The unique aspects of each rating system influence the overall approach to sustainability each promotes. Contrary to the other rating systems’ definition of social sustainability, CEEQUAL does not consider the social acceptability of the project itself as a part of social considerations. In Greenroads, the use of multiple paths to accrue points within the same credit increases the flexibility of the rating system, but the goals of each path are not always the same. For example, in UC-6 Lighting and Controls, points can be earned either by reducing light pollution or by installing energy, water, and air quality monitoring systems, which speak to different goals and different results. For the Greenroads mandatory credits, however, the goals are clearer. Mandatory credits worth no points lay the foundations of a sustainable project, and suggests that any sustainable project must meet minimum performance levels. Similarly, IS’s use of credits that have an environmental foundation and triple bottom line sustainability at the highest level shows a priority for environmental sustainability and clear pathways to TBL.

The environmental sustainability points of each rating system are spread across different types of impacts. This means that a certified project, especially at the

upper levels, would need positive interactions with the environment in many areas (e.g. land, water, energy and GHG emissions) but also means that exceptional performance in one area (e.g. GHG reductions of 80%) would not be enough for certification. This incentivises a broad/shallow rather than specific/deep approach to addressing the significant environmental impacts of infrastructure projects. At only 10% of available points, GHG emissions, potentially the most pressing sustainability issue of our time could be ignored in even top level certified projects.

IS is the only examined rating system that can include consideration of the operational impacts of the infrastructure. Operational impacts can have significant economic, social and environmental consequences. For instance the cars that will drive on a road are the dominant environmental impact of building a new road [38]. By only examining the impacts of design or construction the other rating systems would miss most of the environmental impacts of a road, for instance.

The examined rating systems present a broad approach to examining the sustainability of infrastructure projects. The different structure of each rating system promotes unique approaches to sustainability. The possibility of achieving certification through credits from only 1 or 2 buckets undermines the TBL approach to sustainability and particularly at the lower levels of certification could lead to exclusion of environmental impacts, the original genesis of the move towards sustainable development. The Greenroads approach to mandatory credits demonstrates a productive way to ensure minimum standards are met in economic, social and environmental aspect of sustainability. The absence of operational and other knock on impacts in the consideration of sustainability mean major social and environmental outcomes of the infrastructure projects are outside the scope of certification. Overall, the examined rating systems are defining infrastructure sustainability as mostly about the environment, social impacts are mainly about traffic and working conditions, and environmental concerns are generally diffuse without a particular focus on a specific environmental concern (e.g. GHG emissions).

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Hygrothermal performance assessment of rain-screen ICF walls in coastal climate

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Abstract:

Insulated concrete form (ICF) walls are known for providing airtight and well-insulated walls. Even though the thermal performance of ICF walls are well documented their hygrothermal performance requires particular attention. The rigid polystyrene insulation in either face of the concrete form can complicate the drying process of the built-in moisture in the concrete. This issue in addition to the high moisture index of coastal climate such as the lower mainland of British Columbia could further hinder the drying process. In this study, the hygrothermal simulation for different wall designs and moisture control strategies are conducted with Vancouver, BC climate. The control strategies are varied based on the impact of location and vapour permeance of air and vapour barriers. Results indicate that smaller thickness of insulation on the outside aids to remove the moisture towards outside and installing low permeance air/vapour barrier systems on the outside prohibits drying and drives the moisture towards inside.

Keywords:

Air Barrier, Hygrothermal performance, ICF wall, Vapour barrier, Moisture management.

1. Introduction

The continuously increasing energy efficiency requirements of the national and British Columbia's provincial building codes demand innovative building materials and envelope designs to attain the energy efficiency requirement. ICF walls are considered as one of the effective energy efficient building envelope systems. ICF walls are polystyrene (EPS or XPS) forms that stack like blocks in which concrete is poured into the hollow core of the block to create walls. A study by the U.S. Department of Housing and Urban Development Office of Policy Development and Research (PD&R) [1] show that ICF walls provide a relatively superior structural integrity, energy efficiency and comfort. However, the data from the study on durability was inconclusive. Several works regarding the energy efficiency of ICF walls can be found in the literature [2-5].

The significantly high initial moisture content of the ICF coupled with the relatively low vapour open insulation layers on both sides makes its drying process slower. In addition, the coastal climate of Lower-mainland, BC is known for its high moisture index. The locations of vapour and air barriers, which are intended to control vapour and air movements within the assembly, will further complicate the heat and moisture transport processes. In general, application of building envelope systems without a thorough understanding of their hygrothermal response may cause moisture-related problems such as thermal and moisture performance degradations, mould growth and occupant health risks, increase in building envelope maintenance and repair expenses, and a need for mechanical ventilation system upgrades.

This paper investigates the hygrothermal performance of ICF walls with two air barrier membrane types: vapor tight (Membrane I) and vapour open (Membrane II) air barrier membranes using an advanced heat-air-moisture (HAM) model called HAMFit [6-7] using Metro-Vancouver, BC climate's annual design data. The moisture management potential of the systems, more specifically the effects of these membranes and their locations on moisture control strategy of different ICF wall designs are investigated.

2. ICF Wall configuration and moisture management strategy

In this study, based on the insulation's thickness and configuration four different wall designs are studied.

These wall designs are:

- A. Wall-1: 2" exterior insulation, 6" concrete and 2" interior insulation (designated in this paper as 2-6-2);
- B. Wall-2: 4" exterior insulation, 6" concrete and 2" interior insulation (4-6-2);
- C. Wall-3: 2" exterior insulation, 6" concrete and 4" interior insulation (2-6-4); and
- D. Wall-4: 4" exterior insulation, 6" concrete and 4" interior insulation (4-6-4);

Six different moisture management strategies are considered based on the type and location of the membranes and drywall painting. Membrane I is a dual vapour and air barrier and the vapor open Membrane II is assumed to have vapour permeance of 20 Perm (1140 ng·s⁻¹·m⁻²·Pa⁻¹). The different locations of these membranes placement, in addition to the drywall paint application generates the following six moisture control strategies:

1. ICF wall with no membrane (base case, Case 1)
2. ICF wall with membrane I on the inside (Case 2)
3. ICF wall membrane I on the outside (Case 3)
4. ICF wall membrane II on the inside (Case 4)
5. ICF wall membrane II on outside with painted drywall (Case 5)
6. ICF wall membrane II on inside with painted drywall (Case 6)

Figure 1 shows a typical rain screen ICF wall design. The wall system consists of cladding (19 mm stucco); 10 mm air gap; Membrane (I or II); exterior and interior EPS insulation (~50 mm or ~100 mm); concrete (~150 mm); interior finishing (13 mm gypsum wallboard with or without paint).

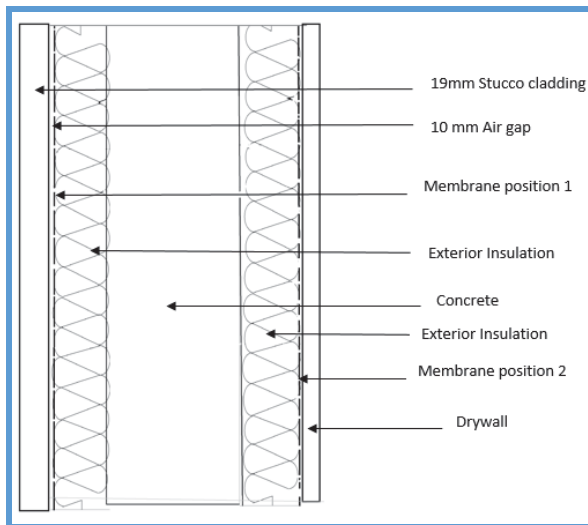


Fig 1: Typical ICF wall components and locations of air/vapour membrane

3. Material properties and the simulation tool

The HAMFit model, an advanced heat-air-moisture (HAM) model, solves the three interdependent transport phenomena of heat, air and moisture in a building component simultaneously. The mathematical model is based on building physics and comprises a set of partial differential equations (PDEs) that govern the individual flows. The transient HAM model has been benchmarked against published test cases [6-7]. The basic material properties required for the input file of HAMFit are taken from the ASHRAE research report [8]. Eight sets of material properties are required for HAMFit simulation, including dry density, air permeability, thermal conductivity, heat capacity sorption and water retention characteristics, water absorption coefficient, vapour permeability liquid permeability.

4. Climate

The weather data is collected at BCIT's Building Science Centre of Excellence weather station at Burnaby campus. The temperature, relative humidity, solar gain and the horizontal rain intensity data was collected in 5 minutes interval and averaged into an hourly data.

The indoor relative humidity is determined using the ASHRAE 160P intermediate model [9] and assuming the building is fairly airtight 0.1 ACH was used. The indoor and the outdoor temperatures used in this study is shown in Figure 2. The indoor air temperatures are set as 21°C and 23°C during heating and cooling season respectively. The rainfall and solar radiation data used in this study are shown in Fig. 3 (a) and (b) respectively.

A one-year simulation was performed for each run. The start date of the simulation was chosen to be July 1 to provide favourable drying period for the freshly built ICF wall systems. The initial conditions of the concrete, EPS and Stucco are set based on simulation results of the walls at 28 days. The resulting moisture content values are taken as initial values of the moisture content. The initial temperature, across the entire cross-section of the wall, is assumed to be 20°C.

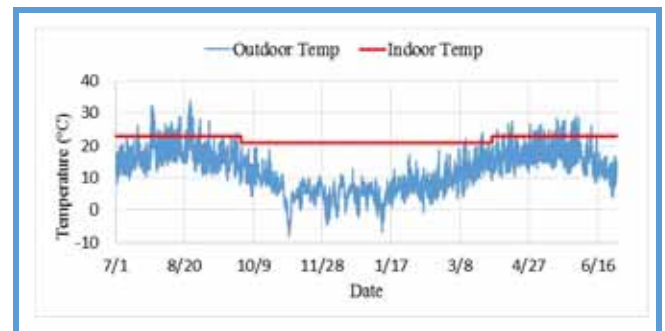
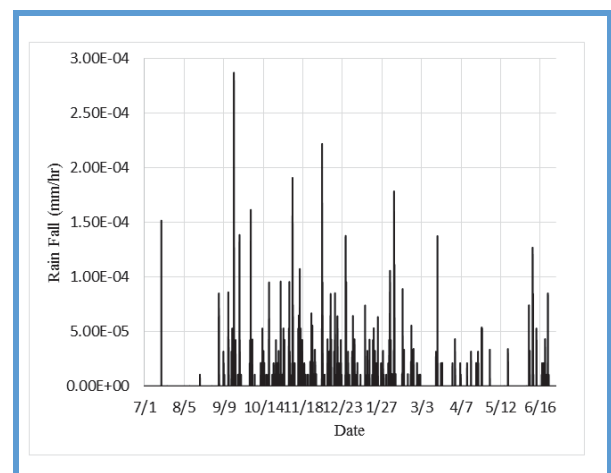
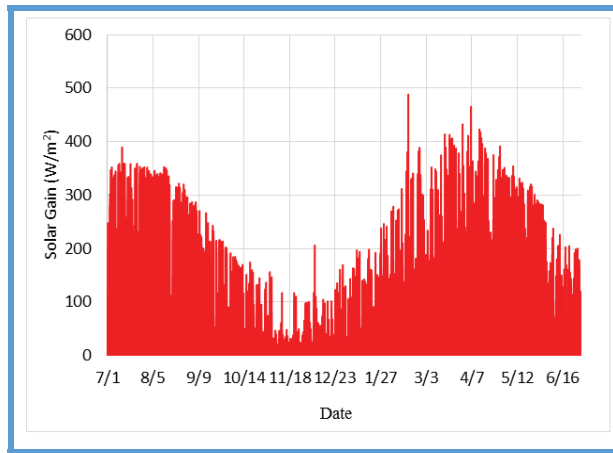


Fig 2: Indoor and outdoor temperature



(a)



(b)
Fig 3 (a) Rain fall data and (b) Solar gain data

5. Results and Discussion

In this section, the simulation results of the four wall designs with different moisture control strategies are presented. The locations of the membranes for each case are shown in Figure 4, in addition, the probe points used to compute the relative humidity and moisture content values are also shown in the same figure.

Figure 5 shows the relative humidity values at the outer side of the exterior EPS, exterior and interior sides of the concrete, the backside and the interior side of drywall of 2-6-2 wall design where the thickness of the exterior insulation is same as the interior insulation. The probe locations are shown in Figure 4.

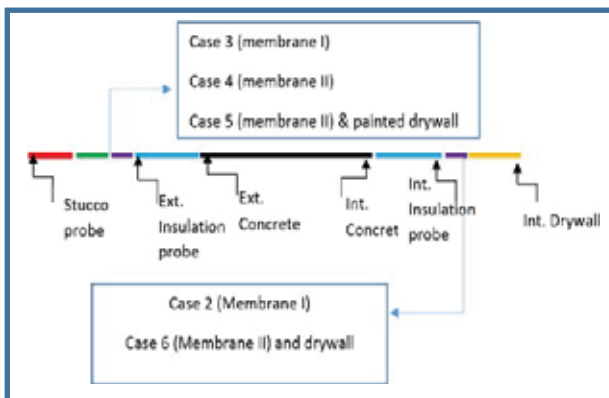


Fig 4: Membrane and other ICF components location

Case 1 is a base line scenario where no air and vapour membranes are used. The interior face of the concrete dries slowly when compared to the exterior face of the concrete. The faster drying of the exterior can be attributed to the air gap between exterior insulation and the stucco cladding and the higher external mass transfer coefficient.

The backside of the drywall registers a higher value when compared to the interior side mainly during cooling season.

Case 2, where Membrane I is placed between interior insulation and drywall, slows the drying of the interior concrete and interior EPS. The interior side of the concrete remains highly wet throughout the year. Both the interior and exterior insulations have a similar relative humidity during the warm season. During the heating season, the exterior insulation retains a much higher RH value. The relative humidity of the drywall remains similar throughout the thickness of the gypsum board.

Case 3, where membrane I is located on the outer side of the exterior insulation, retains the highest relative humidity in the exterior insulation as it is equivalent result in all upcoming wall insulation configurations as well.

In case 4, Membrane II is located on the outer face of the exterior insulation. Since the membrane is vapour open, the moisture migration towards the outside is not stalled. The primary drying path of the concretes is towards the outside. The exterior EPS reaches peak value during winter time.

The Case 5 test scenario is similar to case 4 except the drywall is painted. The RH value of the drywall is elevated and approaches 80% multiple times. The RH value gets higher on the exterior insulation during the cold season. The concrete's drying to outside increases through time. The RH value for the inner face of the interior insulation and the drywall is similar throughout the year.

An air barrier is placed in between the interior EPS insulation and the painted drywall in case 6. The drywall being painted and an air barrier (Membrane II) located on the inside has created similar results to Case 2 for the ICF components (concrete and EPS). The interior side of the concrete remains highly wet throughout the year. The interior insulation has a high relative humidity during warm season as compared with exterior insulation. The relative humidity of the drywall remains low throughout the simulation time. Similar to Case 5, the drywall relative humidity is higher in comparison to Cases 1 to 3.

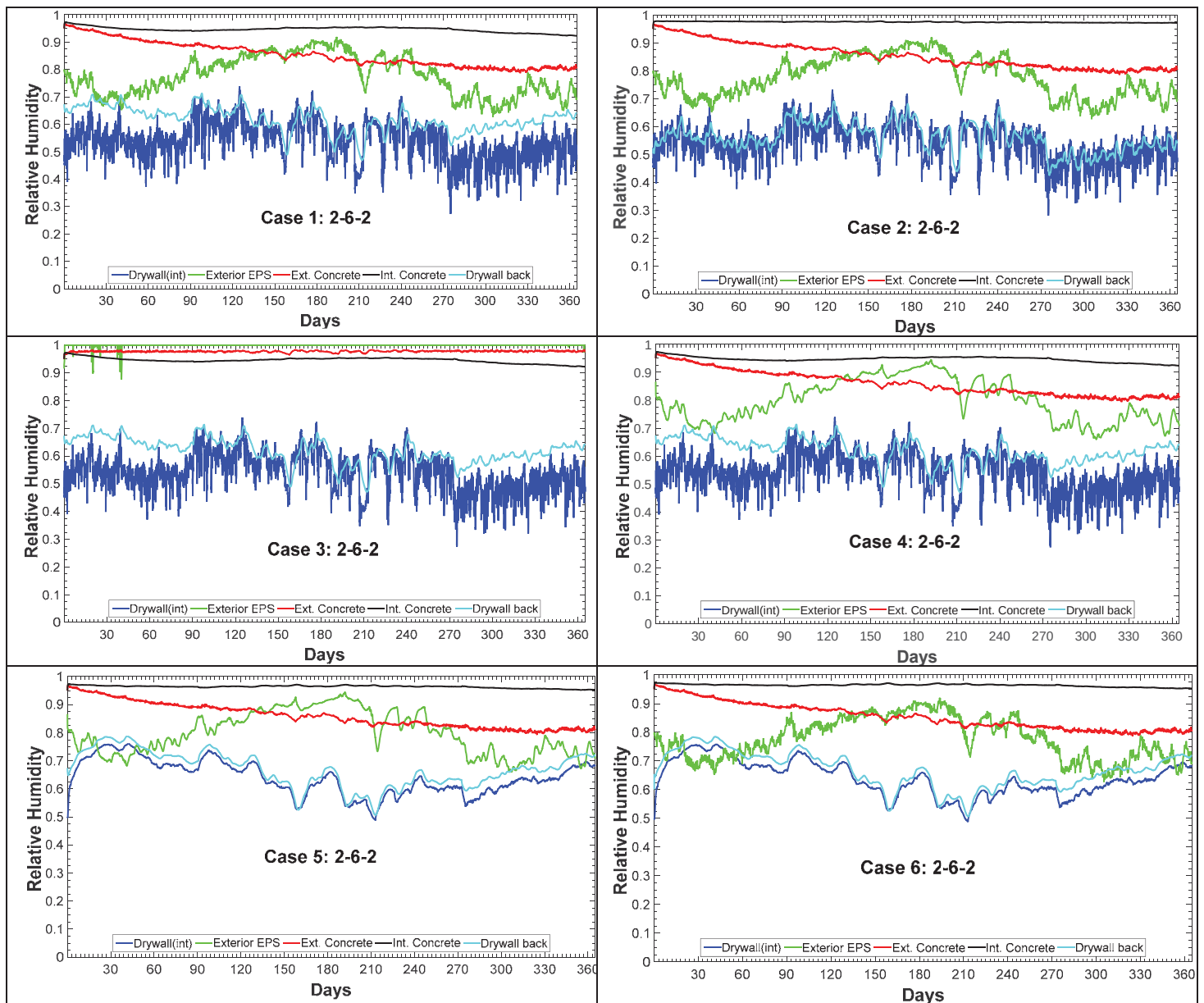


Fig. 5: Relative humidity of 2"-6"-2" wall configuration at different probe points

The other wall designs' performance assessment based on the relative humidity values at the selected probe points shown in Figure 4 are summarized below.

Wall design 4-6-4: Similar to 2-6-2 configuration, Case 3 (where Membrane I is located on the outside) kept the highest amount of moisture in the concrete and the exterior EPS. The exterior EPS' RH value reaches the highest level during winter for the cases 4, 5 and 6. In all cases, the drywall and the interior EPS RH value remains below 80%. The concrete drying process was the slowest of all wall insulation configuration.

Wall design 4-6-2: In this insulation configuration the moisture content of the drywall is the highest of the three wall designs. The exterior side of the concrete dries faster than the interior side of the concrete for cases 1, 2, 4, 5 and 6. Case 3 prohibits the moisture transport to the outside and forces the exterior side of insulation to sustain nearly 100% RH value during most of the time. Also, in case 3, the RH value of the concrete remains constant along the width and its drying process is the slowest. It is fair to assume this effect leads the ICF wall to dry towards the inside and increase the moisture content of the inside wall systems and the gypsum board in later time.

Wall design 2-6-4: In case 2 Membrane I, which is placed between interior insulation and drywall, slows the drying of the interior concrete and interior EPS. The interior side of the concrete remains highly wet throughout the year. The exterior insulation has a high relative humidity during the winter season in comparison to exterior insulation. The relative humidity of the drywall remains low throughout the simulation time.

Case 3 exhibits a similar occurrence as in 2-6-2, 4-6-4 and 4-6-2 wall designs. The relative humidity of the exterior EPS rises at its highest value during winter time. The RH value on the stucco mainly depends on the outside weather condition. The drywall keeps a relatively low RH value throughout the year.

In Case 5, an air barrier is placed on the outer face of the exterior EPS insulation and the drywall is painted. The paint lowers the indoor mass transfer coefficient, thus slowing the drywall drying. The RH value during cold season becomes higher for the exterior insulation. The concrete's drying to outside increases through time. The exterior part of the concrete dries faster.

Case 6, the air barrier is placed between the interior EPS insulation and the painted drywall. The interior side of the concrete remains highly wet throughout the year. The interior insulation has a high relative humidity during the warm season in comparison to the exterior

insulation. The relative humidity of the drywall remains low throughout the simulation time.

The effects of insulation thickness on the hygrothermal performance of an ICF wall are studied using the total accumulated moisture content in the drywall under the different moisture control strategies. Figure 6 shows the drywall's moisture contents of wall designs of 2-6-4, 4-6-2, 4-6-4 and 2-6-2 for the Cases of 1, 2, 3 and 4.

In **Case 1** (no membrane is applied in either side), as can be seen in Figure 6, higher moisture content is observed on the 4-6-2 wall design followed by 2-6-2 envelope. Wall designs 2-6-4 and 4-6-4 show a similar amount of moisture throughout the simulation period. In both walls, the moisture content is smaller wall designs of 2-6-4 and 4-6-4.

Case 2, where membrane I is posted between the interior EPS insulation and the drywall, stabilizes the moisture content under all design cases. The minimum and the maximum registered moisture contents are 0.051 kg/m² and 0.028 kg/m² respectively.

Case 3 and **Case 4**, where Membrane I and II are located on the exterior side of the wall respectively, the moisture content of the drywall exhibits a very similar trend throughout the one year simulation period in both cases. The drywalls of wall designs 2-6-2 and 4-6-2 retain a slightly more moisture content than the 4-6-4 and 2-6-4 wall designs throughout the year.

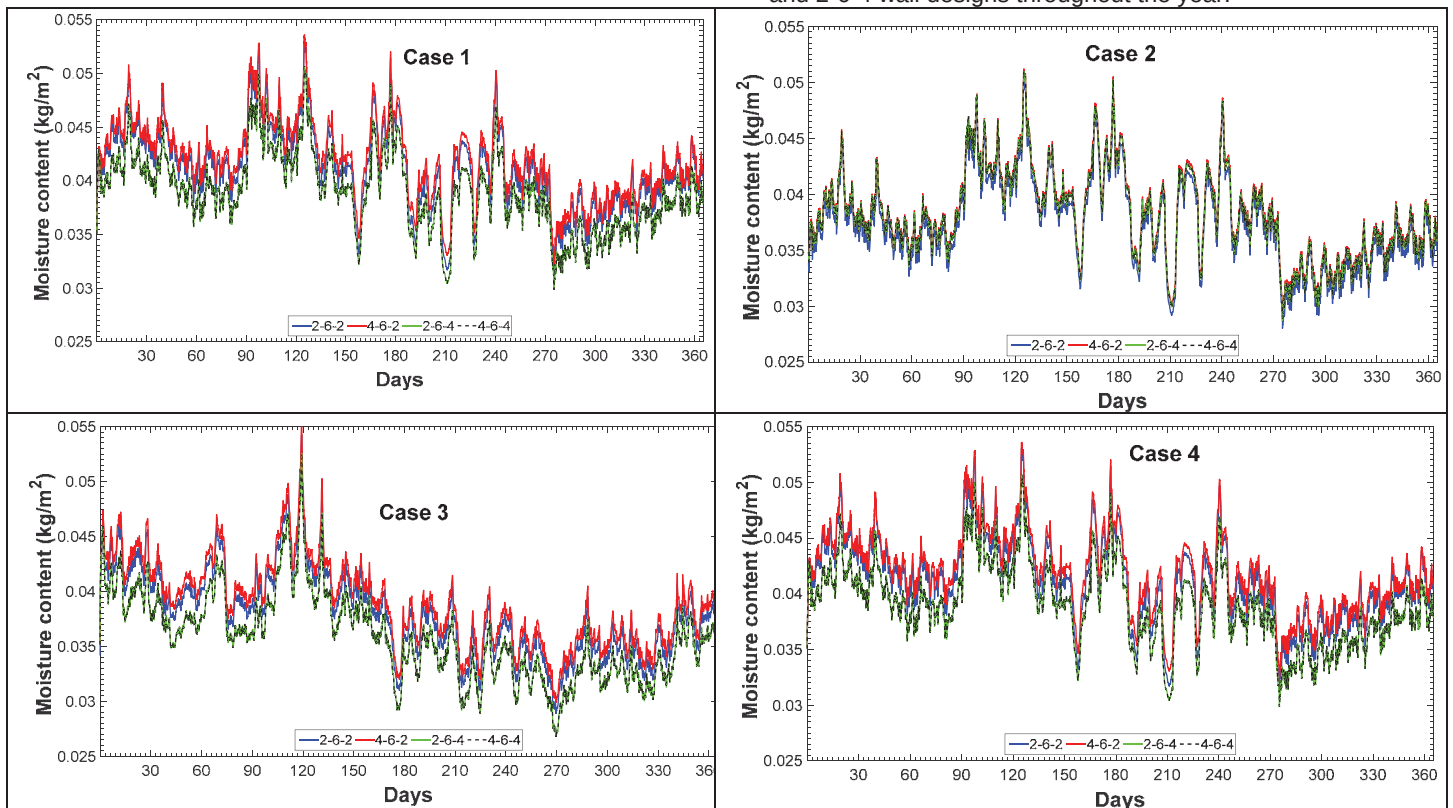


Figure 6. Drywall's moisture content of the four wall designs under different moisture control strategies

Figure 7 shows the moisture content of painted drywall with membrane II located on the exterior and interior side of the ICF wall component. Case 5 and Case 6 moisture control strategies tend to create higher moisture load on the drywall, especially for 4-6-2 and 2-6-2. The increased moisture content in these

strategies can be attributed to the drywall's paint which inhibits the process of moisture drying to the inside. In both cases of 5 and 6, the 4-6-2 model retains the highest moisture content of 0.072 Kg/m² and 0.069 Kg/m².

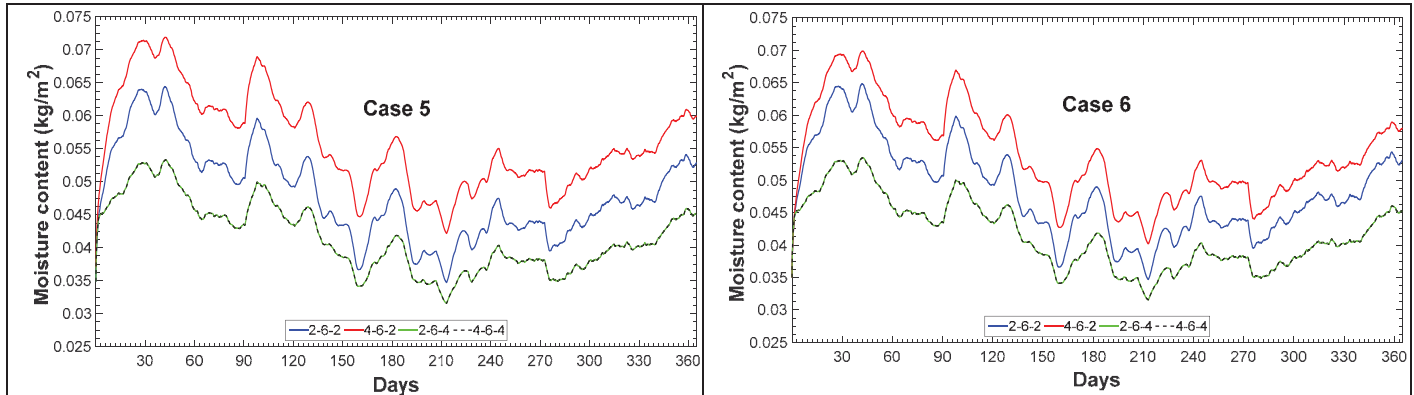


Figure 7. The moisture content of painted drywall of different wall insulation configurations (4-6-4, 2-6-4, 4-6-2, 2-6-2)

In order to find out the optimum moisture control strategy in ICF walls using air and vapour barrier membrane, the relative humidity values on the backside of the drywall are compared. The reason behind selecting this specific probe is because wet drywall creates problems like

mould and rot which can harm the structural integrity and cause mold-related health issues.

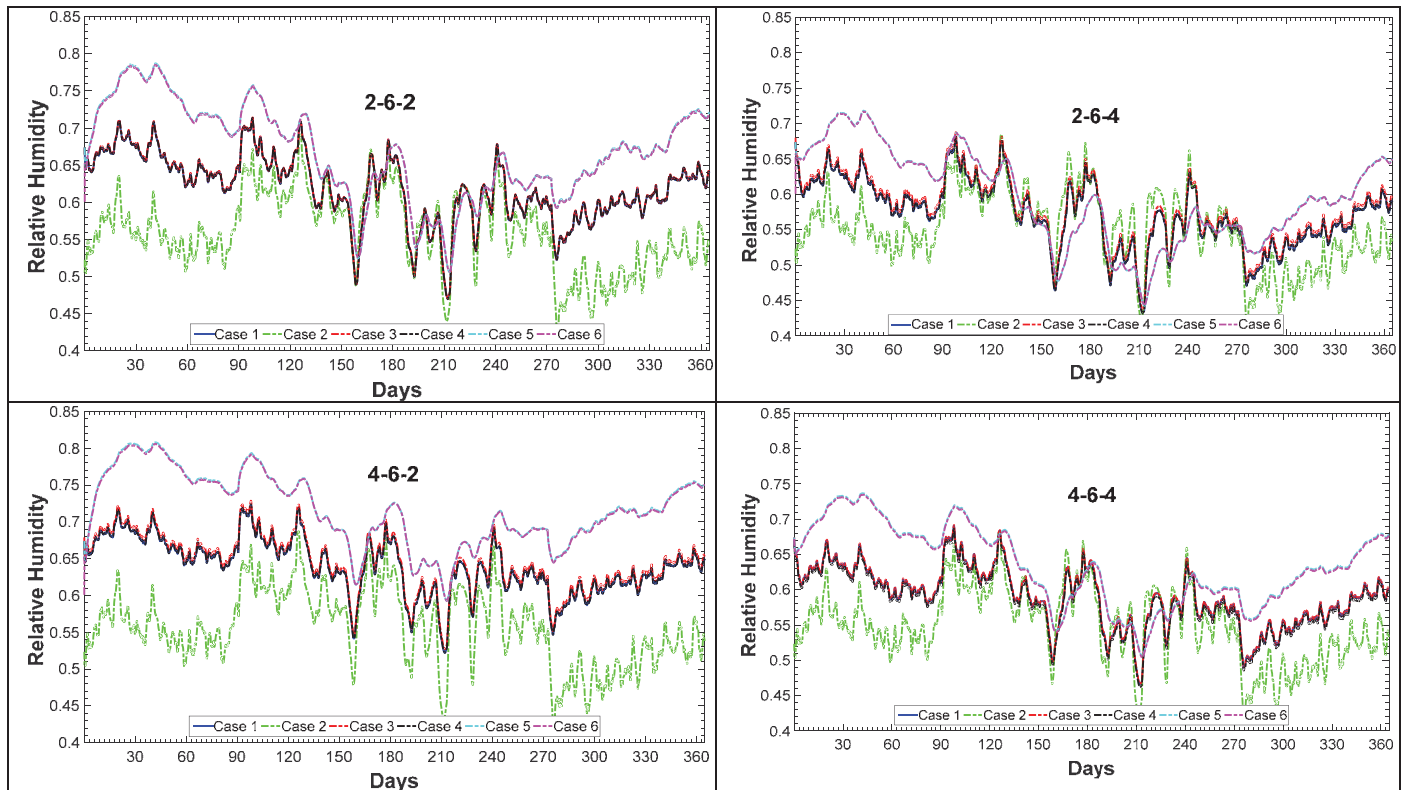


Fig 8: Interior side of the Drywall RH values for different wall insulation configurations

Thus minimizing the relative humidity of the drywall is paramount importance from moisture control strategy perspective. The relative humidity of the drywall in most cases remains below 80% as shown in Fig. 8. In all wall configurations case 2 retains a minimum amount of moisture. Cases 5 and 6, on the other hand, subjected the gypsum board to the highest moisture accumulation

of all other moisture control strategies.

In addition to the RH values on the drywall, the total moisture content of concrete within a year under different moisture mitigation strategies is examined and presented in Figure 9.

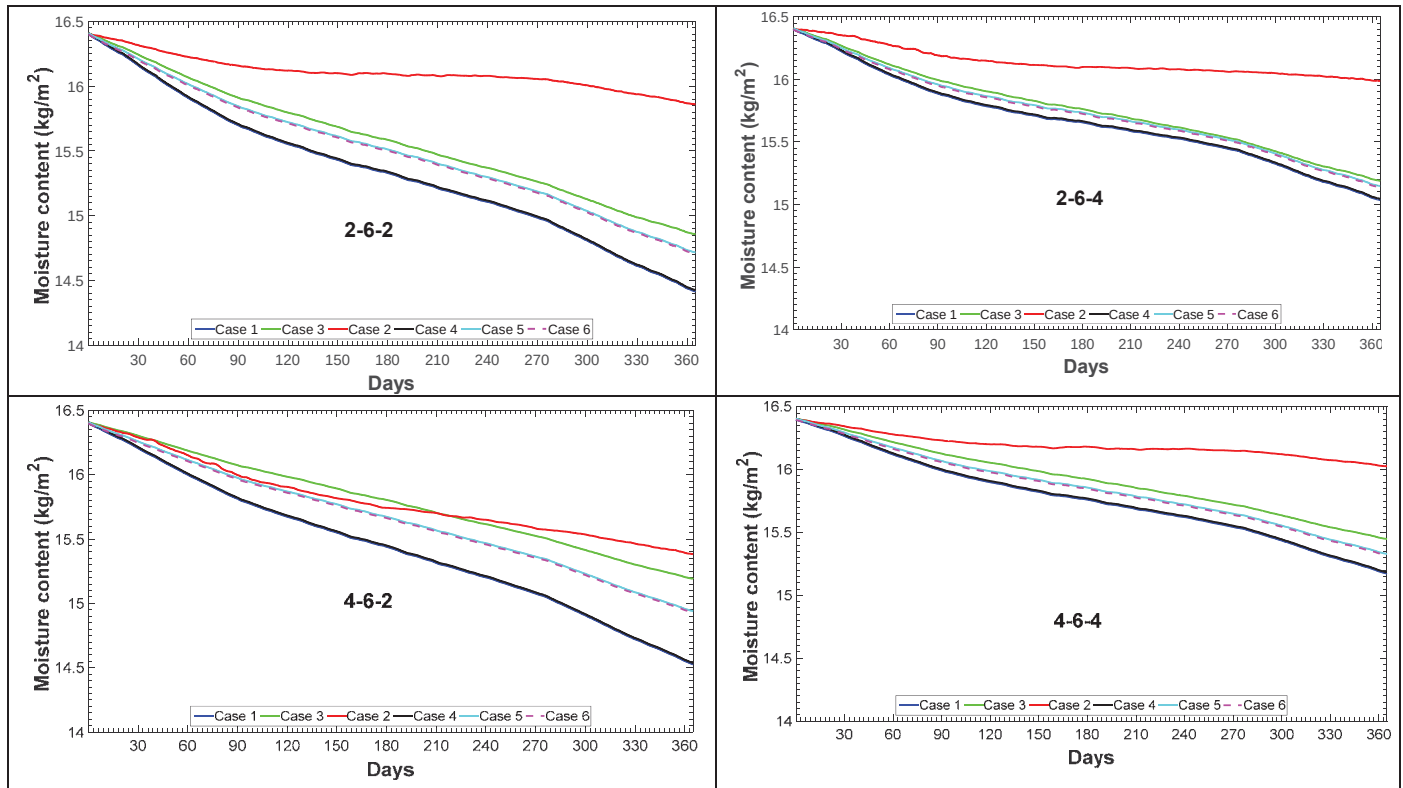


Fig 9: Total moisture content of concrete for different wall insulation configurations

Case 2, as shown in Figure 9, has the slowest drying process of the concrete moisture. In all cases, the 2-6-2 design dries faster than the rest of the walls. For example, Case 2 in the 2-6-2 design dries twice faster than Case 2 of 4-6-4 design. In all wall configurations, Cases 1 and 4 follow a similar drying profile. The concrete in Case 1, when there is no membrane, dries fastest in all cases. Case 2 has shown the least amount of moisture drying.

6. Conclusion

Based on a one-year simulation of four types of wall configurations under six different moisture management strategies, the following conclusions are made. In Case 2, walls with membrane I located on the inside, the drywall is protected from getting wet but the moisture transport from the concrete is slower and one directional: towards the outside. Putting Membrane I on the outside blocks the outward drying process and forces the concrete to remain wet. On the contrary, locating Membrane II on the exterior side wall prevent an incoming wind driven moisture from the outdoor

environment while allowing the wall drying to the outside.

The findings show that increasing the thickness on either side of the concrete slows the concrete drying process. Thus, the 2-6-2 wall design dries the fastest. A 4" EPS insulation on the back of concrete helps the drywall from getting wet. However, a 4" insulation in front of concrete slows the moisture transport towards the outside and has a negative impact on moisture removal strategy.

Applying a vapour barrier on the inside part of the envelope helps to minimize the drywall moisture. However, applying a vapour barrier as a form of drywall paint traps the incoming moisture in the gypsum board.

Acknowledgments

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Coefficient of permeability of cement-based repair materials

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Abstract:

Concrete repair materials are being widely used to restore and extend the service life of structures. While most cement-based repair materials are compatible with concrete structures, their permeability is believed to play a major role in determining the durability and success of the repair. Permeability of repair materials is directly related to ingress of aggressive substances that degrade material properties. In this paper, various direct and indirect permeability testing methods are reviewed and compared with respect to their advantages and limitations. Results of water penetration and rapid chloride permeability (RCP) test methods are selected to evaluate the permeability, in conjunction with the resistance to chloride ion penetration of three types of commercially available cement-based repair materials. These repair materials can be further classified as cementitious concrete modified by 5% silica fume, polymer-modified cementitious concrete, and cementitious concrete, which in this paper are symbolized as mix F, P and M respectively. RCP test results showed that material P had the best resistance to chloride penetration, while the results from permeability test indicated that material M had the lowest permeability in the context of 28 curing ages. It was also found that the temperature increase of the solution during RCP test was proportional to the rate of chloride ion penetration. However, further investigation is required to study the correlation between RCP and permeability test results of repair materials.

Keywords:

Permeability, chloride ion penetration, concrete repair materials

1. Introduction

Concrete repair materials are being widely used to restore and extend the service life of structures. In practice, most repair materials are typically cement-based, polymer-based or a combination [1], [2]. However, like normal concrete, repair materials can deteriorate due to carbonation, sulfate attack, acid attack, etc. Therefore, the search for reliable, long-lasting repair materials for damaged concrete structures is becoming more intensive.

The durability of concrete is influenced by several factors among which permeability and diffusivity play an important role. These two parameters determine the penetration rate of aggressive substances into concrete and how fast degradation could take place [3]. The diffusivity of concrete is dependent upon the ion concentration gradient, while the permeability is affected by a combination of pressure gradient and capillary suction [4]. However, both parameters were found to be dependent on pore structures and the interconnectivity between the pores.

Measuring permeability and diffusivity of chloride ions are important tasks in structural health monitoring practice. Permeability testing methodology can be classified into direct and indirect approaches based on its theoretical basis [3]. The direct testing method is based on Darcy's Law or its modified expressions which use the steady-state assumption [5]. The indirect

methods correlate permeability measurement with the material properties such as bulk expansion [6]–[8] and pressure drop in samples [9], [10], thereby the permeability can be calculated indirectly. Diffusivity of chloride ions can be evaluated by methods such as RCP test method, surface/bulk resistivity test, 90-day salt ponding test, etc.

The coefficient of permeability k_w and diffusion coefficient D_c are two important factors used to quantify the permeability and diffusivity of materials. It was found that diffusion coefficient and water penetration had a non-linear relationship, but more investigations are needed to validate these results for various testing conditions [4], [11].

In this paper, three commercially available cement-based repair materials are studied in terms of their permeability and the resistance to chloride ion penetration. Commonly used test techniques, as well as their advantages and disadvantages, are reviewed first, and the classification of the repair materials is detailed.

2. Literature Review

For cement-based repair materials, cement is the main constituent which may be supplemented with polymer, silica fume, fly ash or any other materials as admixtures [1]. In addition, cement-based repair materials are subcategorized into cementitious concrete and

polymer-modified concrete materials by some researchers due to the large changes brought by the involvement of polymers [12]. The polymer in concrete serves as a water reducer to produce a compound with good workability and lower shrinkage at lower water-cement (w/c) ratios.

In our research, three commercially available cement-based repair materials are investigated in terms of their permeability and resistance to chloride ion penetration. For direct permeability testing, Darcy's Law is the theoretical basis according to which, water flux in pore networks is equal to the product of the coefficient of permeability and pressure gradient. Darcy's Law can be written in the form below [13], [14]:

$$J = -\frac{k}{\eta} \nabla P \quad (1)$$

$$J = k_w \nabla h = -\left(\frac{k \rho g}{\eta}\right) \nabla h \quad (2)$$

where

J	=	flux of the flow
k_w	=	coefficient of permeability
P	=	applied pressure
η	=	dynamic viscosity
h	=	water head
g	=	gravitational acceleration
ρ	=	fluid density

The coefficient of permeability k_w can be expressed as a product of k and the fluid properties, as well as the gravitational acceleration. The direct method evaluates permeability by measuring the flow rate through the porous material under a pressure gradient. The testing apparatus for the direct method is relatively simple and easy to be performed. However, testing process of direct method is usually time-consuming due to the steady-state assumption and it may take several days or weeks to make measurements. In contrast, indirect testing techniques can cut down testing time to minutes or hours by correlating permeability to other material properties. Table 1 reviews some commonly used direct and indirect methods for measuring permeability and their characteristics.

For measuring the chloride ion penetrability of the concrete, there are multiple methods that have been widely used such as RCP test, surface/bulk resistivity test and 90-day salt ponding test.

The underlying theory of chloride diffusion is Fick's Law according to which one-dimensional chloride penetration can be expressed as:

$$J = -D_{eff} \frac{dC}{dx} \quad (3)$$

$$\frac{\partial C}{\partial t} = D_{eff} \frac{\partial^2 C}{\partial x^2} \quad (4)$$

where,

J	=	flux of chloride ions
D_{eff}	=	effective diffusion coefficient
C	=	concentration of chloride ions
x	=	longitudinal distance

Fick's first law shown in Eq.3 is applied in the context of steady-state conditions in which the chloride ion concentration is constant. Fick's second law as shown in Eq.4 is used for non-steady conditions when concentrations are changing.

Whiting [15] first introduced the rapid chloride permeability test which measures the total electrical charge of concrete specimens when a potential difference of 60 to 80 volts DC is maintained across the specimen for 6 hours. This test is one of the short-term procedures most widely used to assess concrete durability and its results correlate well with 90-day salt ponding test. However, test results are affected by the chemical composition of specimens such as the involvement of calcium nitrite as well as temperature of the solution [16]–[18]. Surface/bulk resistivity techniques measure the electrical resistance by inducing an electrical current through concrete samples. This method correlates well with the test results obtained from RCP test and it has the advantage of getting the results in a few hours. The criticism of this method is that test results vary significantly with the degree of saturation of the sample and the pore solution with unknown conductivity may give misleading results [17], [19]. The 90-day salt ponding test measures the depth of chloride ion penetration as one side of a cubic specimen is ponding in a 3% NaCl solution while the other side is exposed to air with 50% relative humidity. This method is one of the most widely used methods of determining chloride ion penetration, though it has several limitations such as extremely long testing process (118 days) and the unsuitability for high strength concrete [17].

Based on the foregoing review, it is found that direct test methods for permeability has relatively simple apparatus and is easier to interpret the results, but is constrained by the steady-state assumption of Darcy's Law. The indirect methods do not require the steady-state flow condition but are more difficult to correlate with permeability. Both methods for measuring permeability and chloride ion penetration are found to change the pore network of the specimen, which could result in measurement errors.

3. Experimental and analytical methods

3.1 Sample casting

In this paper, mix F, P, and M are studied and they can be classified as cementitious concrete modified by 5% silica fume, polymer-modified cementitious concrete, and cementitious concrete respectively. For sample preparation process of RCP and permeability test, only potable water is added to produce the mixes with the desired workability. According to the datasheet, no additional aggregates and admixtures are required.

Table 1: Direct and indirect permeability test methods

	Method and principle	Application and advantage	Limitations
Direct method	Water penetration test – correlate permeability with water penetration depth	Simple testing apparatus; easy to interpret test results	Steady-state flow condition is hard to attain [4]
	Radial flow through test (RFT) – Pressurize water into hollow cylindrical samples and calculate permeability based on internal fluid level	Good repeatability; low potential leakage; High accuracy due to large contact area	Samples need to be fully saturated with water; Sample preparation is difficult [3], [20], [21]
	Centrifuge technique – calculate coefficient of permeability by measuring steady-state unsaturated flow in a centrifugal field	Applicable for materials whose permeability ranges from 10^{-6} to 10^{-13} m/s; Easy to adjust by simply changing the speed of rotation	The sample can be damaged if rotational speed is too high [3], [22]
	High-pressure triaxial cell – Correlate water inlet and outlet with confining pressure to calculate permeability	Capable of measuring permeability of high-performance and high-strength concrete; Variability of replicate results is low	High pressure may introduce artificial cracks [23], [24]
Indirect method	Dynamic pressurization (hollow/solid) – correlate permeability with concrete cylinder expansion under hydraulic pressure	Short testing time; applicable for both high and low permeability samples	Test method for solid cylinders is not suitable for specimens with high permeability [3], [6]
	Beam bending test – Permeability is a function of the rate of change of the forces that sustain the deflection of the beam	Permeability can be measured in a few hours; high pressure is not needed during the test; water leakage does not affect results	Difficult to perform due to the risk of creating cracks during bending test [25], [26]
	Thermal expansion kinetics – Correlate permeability with elastic modulus of the network, the compressibility of the liquid, and the difference between the thermal expansion coefficients of the solid and liquid phases when the concrete is heated	Particularly applicable for measuring very low permeability; can avoid the problems of leakage	Not suitable for materials whose full saturation state is hard to obtain [7], [8]

Table 2: Mix design information

Material	W/C (permeability)	W/C (RCP)	28-day Compressive strength (MPa) (average)	Working time (min)
Mix F	1:10	1:10	45	30
Mix P	1:4.67	1:6.19	62	45
Mix M	1:10.2	1:11.4	50	6

However, due to the fast-setting characteristics of repair materials, samples for RCP and permeability test were cast separately. The w/c ratio for test samples and some key characteristics are listed in Table 2. Samples for RCP test were cast into 100mm-diameter by 200mm-height cylinders, while for permeability test were cast into 150mm-diameter by 200mm-height cylinders in accordance with ASTM C1202 and DIN 1048 respectively. After 24 hours of casting, samples were demolded and placed into a water tank with $23^{\circ}\text{C} \pm 2^{\circ}\text{C}$ for 28 days.

3.2 RCP test

For RCP testing, after 26 days of curing, specimens were moved out of the water tank and sliced using a wet tile saw into the size of 100mm diameter and 50mm long. It should note that the top surface of the cylinder, which serves as the datum plane, was first ground so as to attain the desired flatness. Each surface being cut was further polished on a grinding machine for two minutes for a better surface finish. The cutting and

grinding processes are shown in Fig 1. In addition, the side surfaces around the circumference of concrete disks were coated with epoxy resin to keep chloride ion penetration one-dimensional.



Figure 1: Picture of cutting and grinding processes

Since concrete is a nonconductive material, water is used to saturate the specimens to increase the transportation of chloride ions. At 27 days of curing, a vacuum chamber was employed to extract the pore solution from the specimens. A vacuum pump, which

can maintain a pressure of less than 6650Pa, was connected to the chamber and was running for 3 hours to fully evacuate the vacuum chamber. The distilled water was then injected into the vacuum chamber and submerged the samples while keeping the vacuum pump running for an extra hour. The specimens were left immersed in water for 18 ± 2 hours after which the specimens were ready to be tested. The test setup is shown in Fig 2. It should be noted that a desiccant bottle was mounted between the vacuum chamber and the pump in case the water goes into the pump.

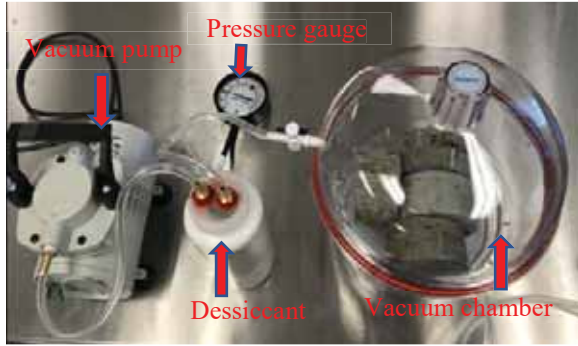


Figure 2: Picture of water saturation setup

On the testing day, specimens were transferred to the RCP testing cells. In our test, we used Giatec Perma2 RCP testing setup which consists of a data acquisition box (DAQ) and four testing cells, as shown in Fig 3. One surface of the specimen was in contact with 3% NaCl solution while the other was exposed to 0.3 normal NaOH solution. A 60-volt DC potential was maintained across the samples for 6 hours during which the electrical current passed and the temperature change were recorded. The total electrical charge in Coulombs during the 6-hour period was regarded as an indication of the resistance of the samples to chloride ion penetration as per ASTM C1202.

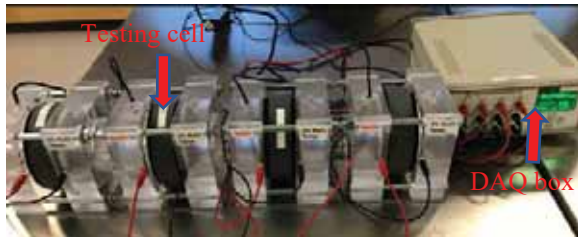


Figure 3: Picture of RCP apparatus

3.3 Permeability test

The water penetration test was performed on six specimens at a time using the apparatus as shown in Fig 4. A water pressure of 5 bar (0.5 N/mm^2) was imposed on the bottom surface of the specimen for three days as per DIN 1048 standard. This pressure was generated by means of the pressurized nitrogen gas applied to the burette, and was monitored and controlled through the pressure gauge and a regulator. In case of water leakage, a rubber gasket with 100 mm

diameter was placed under the specimen and some silicone grease was applied to the gasket surface to further increase water tightness. After 3 days of water penetration, the cylindrical specimens were split into two halves using a compression machine and the penetration depth was marked.

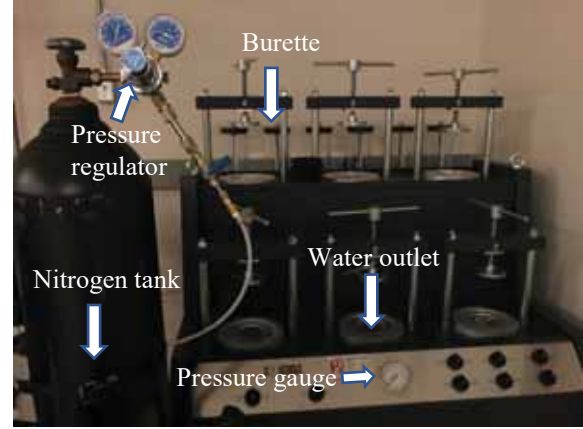


Figure 4: Picture of water penetration apparatus

3.4 Coefficient of permeability

The coefficient of permeability can be calculated using the water penetration results. According to modified Darcy's Law [4], the depth of penetration can be expressed as:

$$\frac{dx}{dt} = k_w \frac{h}{x} \quad (5)$$

where x represents the depth of penetration (m), t indicates the experiment time (s), h is the water head (m), k_w is the coefficient of permeability. By integrating the equation and plugging in the initial condition, that is,

$$x(t=0) = 0 \quad (6)$$

the k_w can be obtained as shown below:

$$k_w = \frac{x_t^2}{2ht} \quad (7)$$

However, the penetration depth is not uniform across the sample's cross section. It is not rational to use the maximum penetration depth because according to Darcy's Law, there should be no difference in penetration depth. Therefore, the average penetration depth was employed and the equation is shown below:

$$x_a = \frac{A}{W_{\max}} \quad (8)$$

where A represents the wetted area, $W_{\max}$ is the width of the wetted area, and x_a is the average depth of penetration.

4. Results and discussions

4.1 RCP experimental results

The resistance of three types of concrete repair mixes to chloride ion penetration is evaluated by computing

Table 3: Rapid chloride permeability test results of three mixes

Material	Type F				Type M				Type P			
No.	I	II	III	IV	I	II	III	IV	I	II	III	IV
Charge (Coulomb)	1275	2373	2879	2755	1399	1379	1389	1419	749	903	762	773
Average (Coulomb)		2669				1396.5				796.8		
Standard deviation		9.88%				1.22%				8.98%		
Temp. Difference		17 °C Max.				9 °C Max.				2 °C Max.		

the total electrical charge during the 6-hour RCP test. The cumulative electrical charge, which geometrically indicates the enclosed area of the curve and coordinate axes, is obtained by integrating the current value with respect to time. The total electrical charge of three mixes are summarized in Table 3. It was found that specimen number two, three and four of Mix F had consistent results whereas the electrical charge of sample one was only half of the other samples. This discrepancy was later found to be as a result of the poor lead connection and was fixed before conducting the following RCP test.

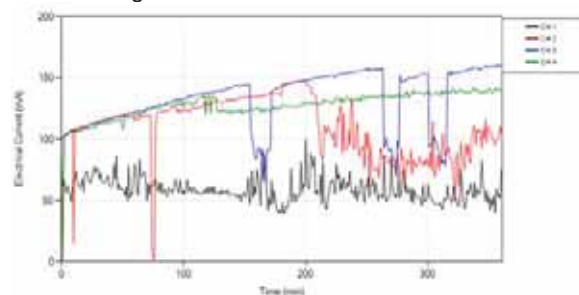


Figure 5: current (mA) vs. time (min) of mix F

The average electrical charge of mix F is 2669 coulombs, which according to ASTM standard C1202, can be classified as having “Moderate” chloride ion penetrability at 28 days of curing. For type M repair material, current vs. time curve is shown in Figure 6. It can be observed that all four channels displayed consistent current values over the 6h period and these values were lower than those obtained from type F samples. It should be noted that the maximum temperature difference of type M was 9 °C which is also lower than type F.

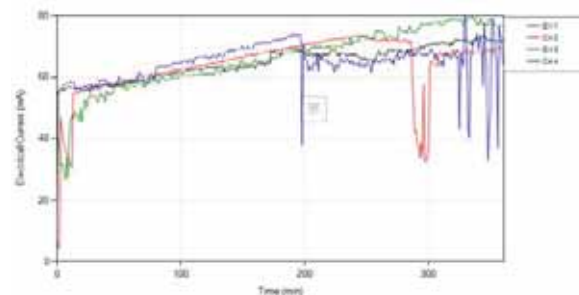


Figure 6: current (mA) vs. time (min) of mix M

Similarly, the cumulative electrical charge of type P samples was calculated to be 796.8 coulombs, which was the lowest among type F and M samples. Accordingly, the maximum temperature difference among four specimens is only 2 °C for Mix P material. Some key values are summarized as shown in Table 3.

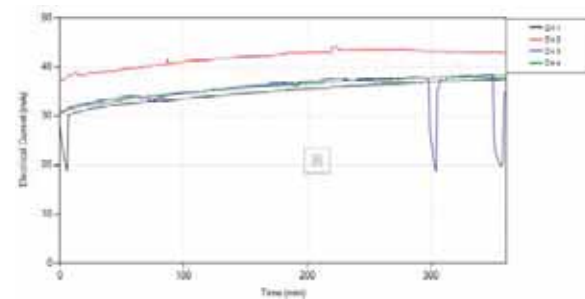


Figure 7: current (mA) vs. time (min) of Mix P

In summary, type P samples indicates the lowest chloride ion penetrability compared with other two repair materials at the context of 28 days of curing. The standard deviations of these three mixes are all lower than the accepted single-operator precision, which is 12.3% in conformance with ASTM C670. In addition, the correlation between temperature rise and chloride ion penetration in this test are in line with the findings from other researchers[17], [27]. Namely, temperature increase boosts up the chloride ion mobility, which in turn will raise the total electrical charge resulting in more heat during the test.

4.2 Permeability test results

The water penetration results of mix F concrete are presented in Figure 8. It was found that the water penetration between two halves was minimal, so the

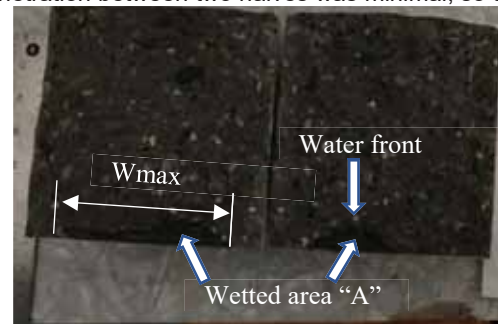


Figure 8: Water penetration of mix F (specimen No.1)

Table 4: Water permeability results

Material	Type F			Type M			Type P		
	I	II	III	I	II	III	I	II	III
Maximum penetration depth $\times 10^{-3}$ m	15	13.5	13.5	7.0	11	6.5	47.5	75	32
Permeability Coefficient $k_w \times 10^{-12}$ m/s	2.83	3.36	3.37	0.76	0.64	0.38	35.2	80.6	10.56
Average $k_w \times 10^{-12}$ m/s	3.19			0.59			42.1		

maximum penetration depth x_f was calculated based on the average of two halves. The coefficient of permeability was calculated by means of the image analysis shown in Fig.9 and Eq. (5) - (8).

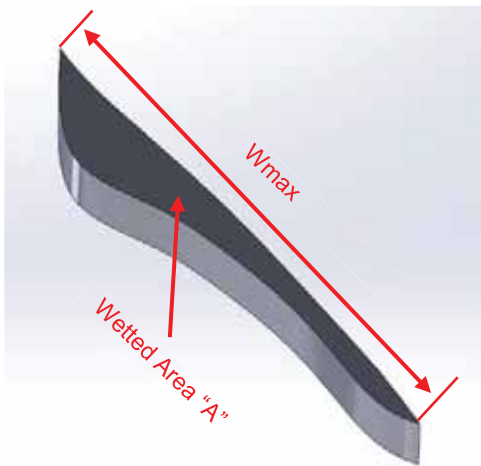


Figure 9: 3D model of water penetration

The test results are summarized in Table 4. It can be observed that Mix M has the lowest permeability coefficient followed by Type F and P, which shows some inconsistency with the findings of RCP tests. Based on the foregoing analysis in the literature review, the chloride ion penetrability should be proportional to the water permeability. There are several factors that could result in this inconsistency which includes different w/c ratio, measurement errors, and image analysis errors. Because of the fast-setting characteristics, repair material samples cannot be cast in large quantities and thus results in the w/c difference for RCP and permeability samples. When measuring the penetration depth of permeability samples, accurate depth values cannot be obtained due to the irregularity of the samples after compression, marker thickness, and collimation errors of locating the waterfront. In addition, the quality of image analysis is largely dependent on the camera position.

It should be noted that the different findings in RCP and permeability could also attribute to the limitations of RCP test. K.D. Stanish et al. [16] reported the chloride

binding effect which affects the rate the chloride penetration during RCP test. Since concrete is not inert to chlorides, chloride ions could physically or chemically bind with concrete especially when the steady-state conditions have not been reached. It was also found that multiple factors can influence the binding capacity of concrete such as chloride concentration, cement composition, temperature, supplementary cementing materials etc. [28], [29].

5. Conclusions and outlook

Based on the results and discussion of RCP test and permeability test, the following conclusions can be made:

The test results show that the type P repair material is most resilient to chloride ion penetration among these three repair materials at curing ages of 28 days. Mix F, M and P respectively can be classified as having “moderate”, “low”, and “very low” chloride ion penetrability as per ASTM C1202.

Temperature variation results of RCP test are in line with the findings from other researchers that the temperature increase of the solution is proportional to the rate of chloride ion penetration

At curing ages of 28 days, mix M shows the lowest water permeability compared with other repair materials, which is inconsistent with the findings of RCP test. Based on the literature review and the foregoing analysis, this difference could result from the different w/c ratio, measurement errors and image analysis errors of permeability test as well as the binding effect of RCP test.

Future investigation is required to validate the accuracy of the coefficient of permeability, RCP test results, and their correlations. More tests can be conducted on these three repair materials with different curing ages, w/c ratios. Other test techniques could also be employed such as surface/bulk resistivity tests, compression/flexural tests, and 90-day salt ponding test to study the capability of repair materials to resist water and chloride penetration.

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Properties and Application of Sheep Wool Thermal and Acoustic Products

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Abstract:

Sheep wool thermal and acoustic material is the new generation 'green and environment friendly' building material. It is mainly made of large diameter sheep wool fibre, which is the 'waste' in normal sheep wool industry. More and more architects, designers, engineers are attracted by sheep wool thermal and acoustic material for its excellent sound absorption, thermal insulation and environment protection characteristics. This paper analyses the sound absorption, thermal conductivity, fire performance and environment protection -properties of sheep wool thermal insulation material, and briefly describes the benefits and application of sheep wool thermal insulation materials in wooden structure houses.

Keywords:

Sheep wool products, Thermal insulation, Sound absorption, Breathable insulation

1. Types and the properties of the sheep wool thermal and acoustic material

1.1 Types

The diameter range of the sheep wool fibre is large. Fine wool diameter is (7~10) μm and the coarse wool diameter even reaches 200 μm . Sheep wool thermal and acoustic material normally made of the sheep wool fibre with diameter about 50 μm . Different kinds of sheep wool thermal and acoustic products are made by batching, mixing, fluffing out, carding, shaping, rip cutting and transverse cutting. According to GB/T 34562 - 2017 'Sheep wool sound absorption and thermal insulation products' Chinese national standard, the products are divided into: Sheep wool thermal and acoustic mat (YZ), Sheep wool thermal and acoustic board (YB), Sheep wool thermal and acoustic pipe (YG).

density and 50mm thickness. There are three kind of installation of the specimen:(a) the mat is pasted on the ground without any air gap; (b) with an 50mm air gap between the mat and the ground;(c) with an 150mm air gap between the mat and the ground.

1.2.2 Thermal insulation

The thermal conductivity test results of sheep wool thermal acoustic mat with 36 kg/m³ density and 50 mm thickness at different temperatures are shown in Data 1. The thermal resistance at different temperatures can be obtained by calculation (Data 1).

Data 1 Thermal performance of sheep wool mat in different temperature

Item	Average temperature / $^{\circ}\text{C}$								
	5	10	20	25	30	40	50	60	70
Thermal conductivity /[W/(m·K)]	0.0354	0.0361	0.0375	0.0382	0.0389	0.0403	0.0417	0.0431	0.0445
Thermal resistance /(m ² ·K/W)	1.41	1.39	1.33	1.31	1.29	1.24	1.20	1.16	1.12

1.2 Properties

1.2.1 Sound absorption property

According to the ISO 354: 2006 "code for measurement of sound absorbing coefficient in reverberation room", Zhejiang University laboratory of environmental physics tested the sound absorption property of Sheep wool sound absorption and thermal insulation mat with 36 kg/m³

Data 2 Thermal performance requirement of sheep wool products

Item	Bulk density ρ (kg/m ³)	Allowable deviation %	Thermal conductivity/[W/(m·K)]	
			Average temperature (25±5)°C	Average temperature (70±5)°C
Mat	16		≤0.046	≤0.058
	20	+15 -5	≤0.043	≤0.053
	40		≤0.037	≤0.046
Board	32		≤0.040	≤0.046
	40		≤0.037	≤0.044
	48	±5	≤0.036	≤0.043
	64		≤0.034	≤0.042
	80		≤0.033	≤0.041

GB/T 34562 - 2017 'Sheep wool sound absorption and thermal insulation products' requirements for thermal conductivity of mat and board products are shown in Data 2.

Comparison of thermal conductivity requirement in the GB/T 11835 - 2007 'Thermal insulation rock wool, slag wool and its products' and GB/T 13350 - 2000 'insulation glass wool and its products' standards shows that the thermal performance of the sheep wool thermal acoustic mat of the same density is little better than that of the traditional rock wool and glass wool thermal insulation products.

1.2.3 Fireproof performance

After testing by National Fireproof Construction Material Quality Supervision Inspection Center, according to the GB 8624-1997 'building materials combustion performance of grading method', sheep wool thermal acoustic board with 8mm thickness is the **B1** level, the test result is shown in Data 3.

Data 3 Fire performance testing result of sheep wool board

Testing item	Testing method	Requirement	Result	Just
Remain length after burning Min/mm	GB/T 8625—88	>0	130	Pass
Remain length after burning Ave/mm	GB/T 8625—88	≥150	167	Pass
Smoke Average temperature/°C	GB/T 8625—88	≤200	150	Pass
Burning head high/mm	GB/T 8626—88	<150	30	Pass
Smoke density level	GB/T 8627—1999	≤75	14	Pass

After testing by National Fireproof Construction Material Quality Supervision Inspection Center, according to the GA 132-1996 'Classification of smoke toxicity of materials', smoke toxicity of sheep wool thermal acoustic mat has achieved **Quasi safety level (ZA3)**: No mice died during 30 min exposure period; Within 3d after exposure to the smoke, the mice did not die, and the average weight recovered.

After testing by National Fireproof Construction Material Quality Supervision Inspection Center, according to term 10.6, 10.9 and 10.10 in the EN 13501-1:2002, the combustion performance grade of

sheep wool thermal acoustic board with 30mm thickness is B-s2, d0. The test results are shown in Data 4.

Data 4 Fire performance testing result of sheep wool board

Item	Testing method	Specimen number	Result
FIGRA ₂₀₀ /(W/s)	EN 13823	3	27.9
FIGRA ₆₀₀ /(W/s)	EN 13823	3	27.1
LFS<试样边缘	EN 13823	3	Yes
THR ₆₀₀ /MJ	EN 13823	3	3.7
SMOGRA/(m ² /s ²)	EN 13823	3	8.2
TSP ₆₀₀ /m ²	EN 13823	3	90.1
Buring drops/Particle	EN 13823	3	No
F ₅ /mm	EN ISO 11925-2	6	30
Filter paper ignition	EN ISO 11925-2	6	No

1.2.4 Environmental protection characteristics

(1) no formaldehyde release

The formaldehyde emission test of the product was carried out by using (9~11) L desiccator method according to term 4.12 in the GB/T 17657 - 1999, a total of 6 samples were tested, including: mat with 37kg/m³ density, 50 mm thickness, mat with 45 kg/m³ density, 30 mm thickness, board with 43 kg/m³ density, 20 mm thickness, board with 92 kg/m³ density, 10 mm thickness, board with 101 kg/m³ density, 14 mm thickness, board with 106 kg/m³ density, 25 mm thickness, Test results show that there is no formaldehyde release.

(2) Good comfort of human body

The main raw material of sheep wool thermal acoustic products is the real natural sheep wool fiber, so persons feel comfortable when they contact with the products directly. Unlike traditional mineral fiber materials, such as glass wool, rock wool, aluminum silicate wool and other products, strongly stimulate the persons' respiratory system and cause skin itching and allergies.

(3) Energy saving and environmental protection in production process

The production process of sheep wool thermal acoustic products mainly includes batching, mixing, carding, shaping, smashing, rip cutting, transverse cutting and packaging with roll. The whole production process does not need high temperature, the production line is short, the power consumption is about 500 kW/h/t, only about 1/3 of rock wool and glass wool products' power consumption.

Sheep wool thermal acoustic products do not produce waste materials such as waste water, waste residue and waste gas in the production process. So the production process is environmental-friendly.

(4) Good usage of the waste sheep wool fibre

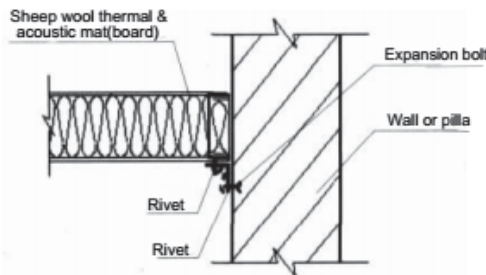
The main raw material of sheep wool thermal acoustic products is coarse wool, which is the waste fibre of wool textile enterprises in carding process. In the process of carding, cashmere accounts for about 10% of the total mass, the wool which can be made into wool fabric accounts for 30%~40% of the total mass, and the remaining 50%~60% coarse wool only can be buried or destroyed by fire. It not only meets the 'turning waste into treasure' commission, but also makes high-tech and profitable products which are favorable to the environment and beneficial to the national energy conservation policy.

2. Application

2.1 Perforated Ceiling system

When sheep wool thermal acoustic mat attached to the back of the traditional perforated ceiling it not only improves the sound absorption performance of the perforated ceiling but also significantly improve the insulation performance of the ceiling system. It obviously improves the comfort of indoor air and save indoor energy consumption.

Installation of flat perforated ceiling is shown in Graph 1.



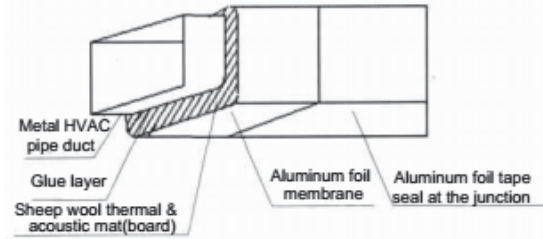
Graph 1 Installation diagram of Sheep Wool Mat behind perforation ceiling tile

Characteristics of perforated ceiling system with sheep wool thermal acoustic mat

- (1) High sound absorption coefficient: NRC up to 0.90;
- (2) Good thermal insulation performance: the thermal resistance R-value reach $1.25 \text{ m}^2 \cdot \text{K/W}$;
- (3) Multi-choice: perforated ceilings for aluminum, FC, plasterboard and other materials; different shape of ceiling, such as plane, chamfer and retainer. Ceilings with various apertures, perforations, and perforations.

2.2 Heating, ventilation and air condition (HVAC) systems

Sheep wool thermal acoustic mat or board with one faced waterproof vapor permeable aluminum foil can be widely used in the heating, ventilation and air condition (HVAC) system, whose construction is shown in Graph 2.



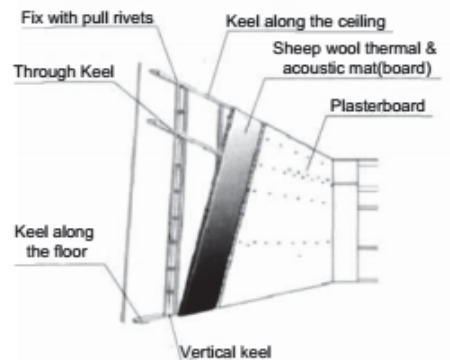
Graph 2 Installation diagram of Sheep Wool MSat in HVAC pipe duct

Characters of heating, ventilation and air condition systems:

- (1) Light weight, the mechanical requirements of the air duct suspension system are low;
- (2) High thermal resistance, excellent thermal insulation performance;
- (3) Easy to install, it does not cause workers itching and strong respiratory irritation;
- (4) Clean and beautiful appearance;
- (5) Safe, environmentally-friendly and sound absorption;
- (6) Long service life, high performance price ratio.

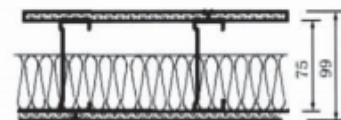
2.3 Light-weight partition wall systems

Sheep wool thermal acoustic mat or board can be used as filling material for light-weight partition wall system, which can significantly improve the sound absorption and insulation performance of the system. The construction opinion is shown in Graph 3.



Graph 3 Installation diagram of Sheep wool mat partition wall system

Structure of the 75 series light steel keel light-weight partition wall system is shown in Graph 4.



Graph 4 Installation diagram of Sheep wool mat 75 Keel partition wall system

The wall thickness of the 75 series light steel keel light-weight partition wall system is 99 mm, inside the

wall filled with 50 mm thickness sheep wool thermal acoustic mat, the thermal resistance of the system is bigger than $1.10 \text{ m}^2\cdot\text{K/W}$, the performance of the sound absorption: The weight loss R_w is 45 dB, the spectrum correction C is -4 dB, and the C_{tr} is -11 dB.

2.4 Sound adsorption and decoration wall system

Sound adsorption and decoration wall system is usually used in the high demand for indoor acoustics places, such as meeting room, cinema, multimedia room and so on. Depends on the customer's requirement different style, different size and shape can be designed, also different color and pattern of the decorative facing can be choose to achieve the unique artistic effect.

According to the GBJ 47-1983 'Reverberation sound absorption coefficient measurement standard', the NRC of the Sound adsorption and decoration wall system is shown in Data 5.

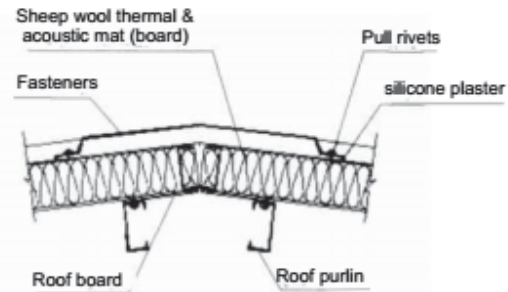
Data 5 NRC of Sheep wool Decoration and Acoustic Panel								
Thickness /mm	Installation method	Octave Centre Frequency Bands (Hz)						Noise reduction (NRC)
		125	250	500	1000	2000	4000	
25	No air gap	0.12	0.23	0.56	1.09	1.03	1.03	0.75
	Air gap 10 cm	0.42	0.69	1.11	1.10	1.13	1.01	1.00
30	No air gap	0.12	0.33	0.79	1.01	1.07	1.11	0.80
	Air gap 10 cm	0.45	0.97	1.10	1.15	1.14	1.20	1.10
50	No air gap	0.27	0.91	1.23	1.29	1.21	1.13	1.15
	Air gap 10 cm	0.58	1.10	1.33	1.19	1.28	1.22	1.20
80	No air gap	0.48	1.19	1.25	1.35	1.19	1.21	1.25
	Air gap 10 cm	0.65	0.95	1.19	1.13	1.01	1.33	1.07

Performance and characters of the Sound adsorption and decoration wall system:

- (1) Environmental-friendly (not release formaldehyde or other toxic gases, without radioactivity)
- (2) Safe (fireproof B1 class, Smoke reaches the safety level, non-toxic);
- (3) Excellent sound absorption, class I absorbent products, NRC is bigger than 0.80;
- (4) Excellent thermal insulation, thermal resistance can reach $1.10 \text{ m}^2\cdot\text{K/W}$;
- (5) Good decorative properties, the color and pattern of the fabric can be decided by customer;
- (6) The size and shape are more selective.

2.5 Steel construction roofing thermal insulation system

Sheep wool thermal acoustic mat can be used in steel construction roofing insulation (Graph 5), the thermal resistance is great, the sound absorption is excellent, beautiful and comfortable, green and safe, meanwhile, it has no any discomfort to the construction personnel.



Graph 5 Steel structure Roof Thermal Insulation System

3. Conclusions and outlook

Sheep wool thermal acoustic material is a real 'whole life' green building material, the fireproof performance can reach B1 level and B-s2, d0 level, according to GB 8624 - 1997 'grading method for combustion performance of building materials' and EN 13501-1:2002 'classification of combustion performance of building products and components - Classification Based on test data reflected by combustion tests'.

Sheep wool thermal acoustic material is mainly made of natural fiber. The fiber has good toughness and is not easy to break. it is safe, environmentally-friendly, and very comfortable. It can be widely used in a variety of residential and commercial buildings because of its excellent sound absorption, thermal insulation, fireproof and environment-friendly characteristics .

References

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- [5] EN 13501-1:2002 'classification of combustion performance of building products and components - Classification Based on test data reflected by combustion tests
- [6] GBJ 47-1983 "reverberation sound absorption coefficient measurement standard

A novel single-target selective disassembly sequence planning method for adaptive reuse of buildings

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Abstract:

Due to the high impact that buildings have on the environment, green design methods are becoming an important part of the building design process. Green design methods have the purpose of reducing environmental impacts and increasing economic benefits in a life-cycle perspective. In this regard, several studies have recognized the importance of the End-of-Life (EoL) stage in buildings and the opportunity of their adaptive reuse as a superior alternative to new buildings in terms of sustainability. The potential benefits of adaptive reuse rely on the fact that it is possible to take away components from an obsolete building and then repair, reuse, remanufacture, or recycle them. Planning for disassembly plays a key role in the adaptive reuse process, where the disassembly planning sequence, as well as the disassembly methods to recover target components, have to be performed in an efficient way. If the design for disassembly is too complex or time-consuming, the associated economic and environmental costs in the adaptive reuse process may outweigh the benefits. The aim of this paper is to describe a new single-target selective disassembly sequence planning method for adaptive reuse of buildings. This study develops the new method using environmental impact, building cost, and rule-based analyses for recovering target components from buildings. The method uses expert rules to choose parts, part order, and part disassembly directions, based upon physical constraints. Contact, motion, and fastener constraints are considered as well. This new model approach is able to improve the environmental-impact and the building-cost performance for the disassembly process depending on the setting preferences. Therefore, it can be used to improve adaptive reuse of buildings.

Keywords:

Selective disassembly planning, Adaptive reuse, Life cycle assessment, Net environmental impacts, Green design methods.

1. Introduction

Due to concerns with the environment, green design methods have become an important part of the building design process. Among such methods are design for assembly, supply chain management, product recovery management, life-cycle assessment, design for disassembly, design for manufacture, disassembly sequence planning, design for adaptability, design for the environment, design for deconstruction, closed materials loops, dematerialization, and closed-loop cycle construction [1-5]. All of them have the purpose of reducing environmental impacts and increasing economic benefits in a life-cycle perspective [1]. In particular, the End-of-Life (EoL) phase has received much attention recently in the construction and manufacturing industries. Several studies have recognized the importance of this stage for buildings and the opportunity for their adaptive reuse as a superior alternative in terms of sustainability [3, 6, 7].

The potential benefits of adaptive reuse rely on the fact that it is possible to take away components from an obsolete building and then repair, reuse, remanufacture, or recycle them. For existing assets, complete design for disassembly is not possible, and the process is reduced to planning for disassembly.

Planning for disassembly plays a key role in the adaptive reuse process, where the disassembly planning sequence, as well as the disassembly methods for recovering target components, have to be performed efficiently. The objectives are to reduce building costs and to increase the building components' life cycle periods. If the planning for disassembly is too complex or time-consuming, the associated economic and environmental costs could be higher than those of installing new components. Studies in the manufacturing industry over the last decade have concluded that disassembly planning can reduce the time and cost associated with product disassembly [1]. It has also been found for the construction and manufacturing industries that the number of disassembly parts affects the EoL recovery profit [8].

The goal of this paper is to develop the framework for a selective disassembly sequence planning method for retrieving target components from buildings. This study develops a new approach by using environmental-impact, building-cost, and rule-based analysis for recovering target components from buildings. This novel disassembly method is based on the Disassembly Sequence Structure Graph (DSSG) model [9]. In selective disassembly planning, finding a global optimum solution even for simple assemblies or

multiple identical building subsystems would be very time consuming and physically impractical [9, 10]. Therefore, in this study an optimized sequential disassembly plan is generated based on expert rules. The disassembly planning is performed one component at a time and by considering specific disassembly/deconstruction methods.

2. Designing for a circular economy in construction

In an era of climate change mitigation and adaptation, efficient use of the earth's natural resources is considered as a practical means to increase sustainability in urban settlements. Buildings contribute significantly to the global environmental load caused by human activities. From a life cycle perspective, the building industry is responsible for about 30 per cent of global annual Greenhouse Gas (GHG) emissions, 40 per cent of energy consumption 32 per cent of world resource depletion, 12 per cent of water consumption, and 40 per cent of waste to landfill [11, 12].

Due to the growing concern for the environment, sustainability has become a requirement rather than just a desirable characteristic for products and services in many industries, including the construction industry. To remedy this situation, this industry is implementing designs and systems with improved long-term life-cycle performance. The main objective is to consider closed-loop circular design principles. Closed-loop material cycle construction (CLMC) can be defined as recovering construction materials and building elements from old buildings and infinitely recycling them through natural or industrial processes [4]. Sassi [4] defined criteria by which building materials can be assessed in terms of forming part of a CLMC, drawing on existing research on natural recovery and design for deconstruction and recycling. According to Kibert [3], themes such as deconstruction, durability, adaptability, design for the environment, design for deconstruction, closed materials loops, and dematerialization are not yet woven into the fabric of sustainable construction, but they certainly play an important role. In their work, Jaillon and Poon [13] concluded that the promotion of a closed-loop material cycle is critical to sustainability, thus minimizing carbon emissions and natural resource consumption. Silvestre, de Brito and Pinheiro [14] demonstrated the importance of assessing waste flows for decision-making at the EoL of building materials so as to maximize material's cradle-to-cradle environmental performance through waste minimization or reuse/recycling operations maximization. Shultmann and Sunke [15] discussed energy savings in terms of embodied energy that could be realized through using different recovery techniques on deconstruction projects. All these studies support the idea that opportunities exist to maximize the benefits of resources during the EoL stage of buildings.

2.1 The role of adaptive reuse in modern construction

In 2010, it was estimated that the total building stock in the United States was approximately 27 billion m², and that 0.162 billion m² of buildings were torn down, while 0.464 billion m² were renovated and/or newly built facilities every year [16]. According to Yudelson [17], approximately 75% of the buildings expected to be operating in the year 2040 are already built. Also, it is well known that the turn-over rate of buildings is considered relatively low [16, 18-20]. Existing buildings approaching the end of their lifespan could become a "mine" of raw materials, since recovering the components through product recovery management is often more efficient than extracting raw materials to produce new ones [11, 15]. In fact, Conejos [16] claims that demolition and equivalent new construction of energy-efficient buildings would require decades to equal the energy savings of rehabilitating and reusing existing buildings. Hence, the greatest natural resources savings as well as the greatest environmental impacts minimization are in retrofitting and redeveloping existing buildings rather than producing new energy-efficient buildings [16, 21], in essence "re-using" existing buildings. Thus, adaptive reuse for buildings has emerged as a broadly growing practice.

Adaptive reuse improves the financial, environmental and social performance of buildings by taking obsolete ones, restoring them, and in some cases, changing their use [11, 22]. As part of its life cycle, a building's operational and commercial performance decreases over the years, until its performance falls below the expectations of its owner, or until a third party perceives a higher potential value in repurposing it. In the past, the owner perceived a number of options at this point, typically its EoL. Common EoL options for a building and its materials are direct reuse, repairing, refurbishing, remanufacturing, cannibalization, recycling, combustion with heat recovery, composting, incineration, and landfilling [15]. However, the decision to choose any of these EoL options may be premature if it ignores the residual utility and value of buildings that could be optimized by "giving them new life" using the process of adaptive reuse. Because of the great impact that the building industry has on the environment, failing to optimize a building's useful life can result in its residual lifecycle value not being fully exploited, thus wasting the embedded resources. Adaptive reuse addresses this potential.

The decision-making processes associated with the planning, design and construction of a building are diverse and dynamic. Therefore, choosing adaptive reuse for a building project is complex as well. The difficulty lies in all the different aspects that have to be taken into account, such as the physical integrity of the building, economic issues, functionality, and technological retrofits. For this reason, little research has been done regarding establishing feasible methodologies for the assessment of adaptive reuse of buildings for example the Adaptive Reuse Potential (ARP) model and the adaptSTAR model [6]. Another

example are the technical regulations and normativities for adaptive reuse, under the name of “smart growth” and “smart codes” [23]. Some authors stress that intuition and experience are the only guides in making decisions about adaptive reuse [24].

2.2 Disassembly Planning in Adaptive Reuse of Buildings

Throughout the process of adaptive reuse, it is necessary to take away components from an obsolete building and then repair, reuse, remanufacture, or recycle them. In this matter, planning for disassembly, or disassembly planning, plays a key role. Disassembly planning consists in finding structured sequences for dismantling an assemblage. A structured sequence is the consecutive order for disassembling a given assemblage, part by part. This field has been studied in the manufacturing industry over the last decade, concluding that disassembly planning can reduce the time and cost associated with disassembling products [1].

According to Smith & Hung [1] the different types of disassembly planning methods can be classified as follows: destructive and non-destructive disassembly planning methods, complete and selective disassembly planning methods, and sequential and parallel disassembly planning methods. The authors explain that destructive methods destroy the functional capabilities of the disassemble components and that selective disassembly planning methods only remove specific high-value parts. In the same way, they explain that sequential methods remove one part at a time, while parallel methods remove multiple parts at the same time. The authors detail the benefits of each method highlighting that selective disassembly planning methods can be used to minimize environmental impacts and economical cost in practical applications if the methods are applied in a proper way.

In their work, Smith, Smith and Chen [9] did an exhaustive comparison between the different approaches applied for sequential disassembly planning, finding that the Disassembly Sequence Structure Graphs method (DSSG) is an optimal approach. The approach is able to create a Disassembly Graph (DG) in minimum time and a minimum-size multiple-target DSSG in minimum time. Also, the approach finds solutions optimized for a number of parts, part order, and part disassembly directions, in minimum time. It is important to highlight that the DSSG method has been developed and successfully applied only in the manufacturing industry [9]. Therefore, there is a lack of knowledge in the development of disassembly planning models for buildings.

3. The knowledge gap

Adaptive reuse of buildings has been demonstrated to be a superior alternative to new construction in terms of sustainability. Nevertheless, its current implementation relies on conventional intuitive planning procedures by professionals in the construction industry, leading to suboptimal results with little quantitative or objective measure.

There is a need for developing a structured strategy that allows the quantification of benefits of adaptive reuse of buildings, through an algorithm method during the disassembly planning stage of building assets. The development of such a method could provide better understanding of the parameters involved in the process of adaptive reuse, in order to improve the benefits and boost its application towards more sustainable development in the building industry.

4. Methodology

Disassembly planning consists of creating a disassembly model and then generating disassembly sequences [9]. A disassembly model is a graph with nodes and links, where the nodes represent the different parts of an assemblage and the links represent the constraints between parts. The parts of the assemblage should be identified as components or fasteners. Graphs are converted into constraint matrices for computing processing. Disassembly sequence planning consists of finding an optimal and feasible path for disassembly. According to Smith et al. [9], the quality and complexity of disassembly models affect the solution quality and searching time. For instance, a model that contains more information improves the solution quality, however a model that contains less information reduces searching time. In their work, Smith et al. [9] demonstrated that their DSSG model approach improves solution quality and searching time for disassembly models in comparison to prior techniques as shown in the literature review. The DSSG model approach optimizes the number of removed parts, part order, part disassembly directions, and reorientations in order to create high quality, practical, realistic, and time-efficient disassembly sequence planning [1, 9, 10]. To find solutions, the DSSG model approach creates a Disassembly Graph (DG) model, then it creates a DSSG model from the DG model based on realistic part disassembly directions and expert rules. According to Smith et al. [9], choosing directions before searching disassembly paths reduces model complexity and searching time, while expert rules ensure that the found solutions are feasible, practical, realistic and efficient.

The DSSG model approach has been developed and successfully tested in several case studies for the manufacturing industry. The DSSG model approach has been adapted in each study to optimize specific goals such as minimizing the search time, minimizing the number of removed parts, minimizing the number of changes on the reorientation for extracting parts, minimizing the amount of labour for disassembly,

minimizing the disassembly cost, maximizing the Recycle Value (RV), and maximizing the cost-benefit of partial disassembly planning with a life cycle impact assessment approach [1, 9, 10]. This paper aims to develop a new disassembly planning approach to be applied for adaptive reuse of buildings. The new graph model should be simple to construct, improve solution quality, minimize complexity, and reduce the searching time for disassembly planning of buildings. Lastly, the new graph model has to be oriented for improving the economic and environmental performance of the disassembly planning process with a life-cycle perspective.

4.1 Building Information Modeling prototype

A simplified typical building frame assembly was modeled through a specialized 6D BIM software for the purposes of this study. The software used was Revit® and the add-in Tally®. The 6D BIM prototype contains the three-dimensional geometry, as well as the physical properties per building component of the model (3D). Also, the 6D BIM prototype contains information concerning the construction phases and work schedule (4D), as well as the cost estimating and budgeting (5D). Lastly, the 6D BIM prototype also contains the information concerning the LCA phases (6D). With the development of an accurate 6D BIM prototype, it is possible to have access to the necessary data for the purposes of this study with a powerful and highly organized graphical interface. Figure 1 shows the configuration of the final 6D BIM prototype under study.

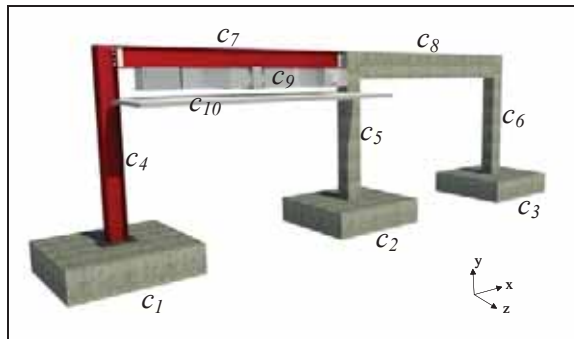


Fig 1: Building frames assembly prototype (C_1, C_2 , and C_3 - concrete isolated foundation 1830x1830x457mm; C_4 - steel column W10X49; C_5 and C_6 - concrete column 120x120mm; C_7 - steel beam W12X26; C_8 - concrete beam 120x200mm; C_9 - Ventilation ducting system; C_{10} compound ceiling 2'x4' ACT System).

According to Smith et. al [9], for assemblies that have horizontal, vertical or round contact surfaces, all parts can be disassembled in four (+x, -x, +y, -y) or six principle directions (+x, -x, +y, -y, +z, -z) without losing generality. The DSSG theory has the flexibility of adding further directions of analysis by expanding the size of the initial matrices [1, 9, 10, 25]. With this simplification, it is possible to reduce the calculation time, as well as the complexity of the algorithms'

improving processes. The two-dimensional representation of the simplified hypothetical building frames assembly under study is shown in Figure 2. This could represent a repeated element of many structural bays in a building.

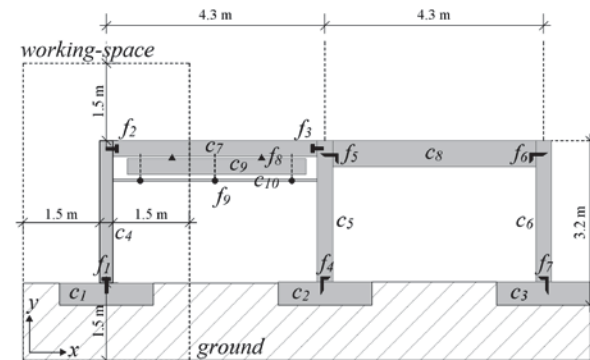


Fig 2: Two-dimensional assembly prototype.

4.2 The disassembly graph model

In this study, a Disassembly Graph (DG) model is represented by constraint matrices, in which columns represent a constraint and rows represent a part under analysis. A constraint can be physical, functional, environmental, or economic. For example, components create physical constraints by occupying volumes, while fasteners create the constraints by connecting components to other components. Matrix columns also indicate the disassembly directions. In a two-dimensional application the disassembly directions include $\{+x, -x, +y, -y\}$ directions. The following matrices are contained in the DG model in this study: a physical constraint matrix for components (PhC), a projection constraint matrix for components (PC), a hosted component constraint matrix (HC), a liaison constraint matrix for components (LC), a contact constraint matrix for fasteners (CF), a motion constraint matrix for fasteners (MF), an environmental constraint matrix for components (EnvC), and an economic constraint matrix for components (EC). The physical constraint matrix is separated into a contact constraint matrix (CC) and a motion constraint matrix (MC).

A contact constraint matrix for components (CC) registers the physical contact between parts. A motion constraint matrix for components (MC) records motion constraints for each part per disassembly direction. Each row element of the matrix contains "first-level working-space parts", parts that intersect with a part's projection inside the working space for extraction works in any given direction. In contrast to a manufactured product, a building has much more space inside for removing parts. That is the reason why is not necessary to include all the "first-level parts" that intersect all the way along the projection of the part under analysis. For this study, it is defined as a "working-space", a reasonable physical space for developing extraction works by a worker using basic equipment or specialized machinery. As an

assumption for the first experiments in this study, the working-space was set at a perpendicular distance of 1.5 meters from the plane of work of the part under analysis in a given direction. As an example, Figure 2 shows the working space defined for the component number four (c_4). It is important to highlight that in contrast to manufactured products, the disassembly of a building has a main movement restriction related to the ground. It is not practical to include component disassembly directions that intersect with the ground. For this reason, the MC also records the motion constraint of each part with the ground. The objective is to leave the possible disassembly directions that overlap with the ground as the last option to analyze. For example, in Figure 2, $MC_1 = \{f_1, f_1, [f_1, c_4], [f_1, ground]\}$. Finally, the CC and MC matrices are combined into a single matrix called physical constraint matrix for components (PhC). The MC matrix for Figure 2 is.

$$MC = \begin{bmatrix} MC_1 \\ MC_2 \\ MC_3 \\ MC_4 \\ MC_5 \\ MC_6 \\ MC_7 \\ MC_8 \\ MC_9 \\ MC_{10} \end{bmatrix}$$

$$= \begin{bmatrix} f_1 & f_1 & f_1, c_4 & f_1, ground \\ f_4 & f_4 & f_4, c_5 & f_4, ground \\ f_7 & f_7 & f_7, c_6 & f_7, ground \\ f_1, f_2, c_7, c_9, c_{10} & f_1, f_2 & f_1, f_2 & f_1, f_2, c_1, ground \\ f_3, f_4, f_5, c_8 & f_3, f_4, f_5, c_7, c_9, c_{10} & f_4, f_5, f_3 & f_3, f_4, f_5, c_2, ground \\ f_6, f_7 & f_6, f_7, c_8 & f_6, f_7 & f_6, f_7, c_3, ground \\ f_2, f_3, c_5, c_8 & f_2, f_3, c_4 & f_2, f_3 & f_2, f_3, c_9, c_{10} \\ f_5, f_6, c_6 & f_5, f_6, c_5, c_7 & f_5, f_6 & f_5, f_6 \\ f_8, c_5 & f_8, c_4 & f_8, c_7 & f_8, c_{10} \\ f_9, c_5 & f_9, c_4 & f_9, c_7, c_9 & f_9 \end{bmatrix}$$

A contact constraint matrix for fasteners (CF) records contact constraints for each fastener^[9]. In other words, in the CF the direction of extraction of the fastener with respect to the component is indicated. For example, constrained fasteners like bolts only have one disassembly direction while unconstrained fasteners, such as washers, can be removed in any disassembly direction^[9]. For a 2D product with n_f fasteners and four-part disassembly directions, the CF matrix has n_f rows and one column. For each constrained fastener, the possible disassembly directions are 1, 2, 3, or 4, which represents a disassembly direction, +x, -x, +y, and -y. For unconstrained fasteners $CF_i = 0$. For example, in Figure 2, $CF_1 = 3$ and $CF_3 = 2$.

A motion constraint matrix for fasteners (MF) records motion constraints for each fastener in the extraction direction defined in CF . Each cell of the matrix contains "first-level working-space parts", parts that intersect

with a part's projection inside the working space for extraction works in any given direction. For a 2D product with n_f fasteners and four-part disassembly directions, the MF matrix has n_f rows and one column. For example, in Figure 2, $MF_2 = [c_9, c_{10}]$ and $MF_8 = [c_{10}]$. For simplification purposes, MF just records components. For unconstrained fasteners $MF = 0$.

A projection constraint matrix for components (PC) registers the intersected components on the projection of each component under study in a given direction and inside of their working space. The approach of this study uses the PC matrix to choose optimized part disassembly directions.

A hosted component constraint matrix (HC) indicates the individual relationship between the host and the hosted components. The component HC_i under analysis is defined as the host component, and the registered elements per host component are the hosted components. For this study, a hosted component is physically attached to the hosting component with a fastener. Also, the static condition of a hosted component depends on the hosting component.

A liaison constraint matrix for components (LC) records the fasteners that physically attach the hosted components to the hosting component under analysis. For a 2D product with n_c components, the LC matrix has n_c rows and one column. For Figure 2, $LC_1 = [f_1]$ and $LC_7 = [f_8, f_9]$.

In the next step, with the information of the HC and LC matrices, the MF matrix has to be completed. The MF matrix contains the components that physically impede the extraction movement of the fasteners. However, for building components sometimes the fasteners do not have extraction movement constraints, but without them the assembly would be unstable. Therefore, it is necessary to add the components located in the next levels of the hierarchical liaison graph into a combined constraint matrix ($MF-HC$). With this approach, the analysis per fastener would be realistic for buildings.

An environmental constraint matrix for components ($EnvC$) contains the information related to the environmental impacts associated with the components in terms of their life-cycle. The calculated environmental impacts are aligned to the specifications of the specialized software Revit® and Tally®. The phases included in the LCA are production stage, construction stage, and EoL stage.

An economic constraint matrix for components (EC) contains the information related to the budgeting associated with the selective demolition or selective disassembly of each component. The component cost for these works was retrieved from the national database RSMeans. RSMeans^[26] estimates average construction costs and productivity rates based on a 30 city average from across the USA. The data recovered

from this database is considered representative for the scope of this study that is the building market in North America. Nevertheless, further investigations should be done in order to adjust the fluctuations of the suggested prices due to particularities of the local economies of the building of emplacement.

4.3 Optimized part disassembly directions

In general, a target component can only be removed in one disassembly direction and it cannot change directions during disassembly. This simplification makes sense, since the present approach also proposes the setting of a limit space for removal works. In buildings, the fasteners can be reached from different directions. In addition, the building components are subject to hosting constraints to keep the physical integrity of the whole structure. Therefore, for this study approach, the best extraction direction for a component is the one that contains the highest number of hosted components and then minimizes one of the objectives of interest (net environmental impacts of the discarded components or the cost of the building works). Avoiding disassembling other components that are not related to the physical stability of the target component reduces the number of removed parts while the best disassembly sequence plan reduces the net environmental impacts or reduces the total cost of the building works, depending on preferences. The approach in this study chooses optimized part disassembly directions before searching for solutions. According to Smith et al. [9] choosing directions before searching reduces model complexity and searching time.

5. Results and discussions – The disassembly sequence plan model for buildings

The proposed model in this study is an inverted tree where the root node represents a target component and the leaf nodes represent the parts that constrain the target component. Taking the model in Figure 2 into account, Figure 3 shows a single-target disassembly sequence plan graph for removing target component c_7 , in the -y direction. The disassembly graph contains seven parts in total. One target component, two other components, and four fasteners. Squares represent

components and circles represent fasteners. Each node has a disassembly direction assigned by the model approach and they are arranged in constraint levels. Fasteners f_2 and f_3 are connected to component c_7 by fastener constraints. Boundary component c_{10} is connected to fastener f_2 and f_3 by a motion constraint. Fastener f_9 does not have any constraints, therefore it can be removed. The approach creates a disassembly sequence by adding nodes from the root nodes to leaf nodes.

The approach for creating a single target sequence disassembly plan gets parts from DG, then it arranges and orders them part by part in levels. The process creates a root node for target component t . By using expert rules, the process assigns a disassembly direction to t . Then, the process retrieves the parts ($p=c'$ or f') that constraint to t in the given direction, puts the parts in a queue, and moves one-part p_n at a time from the queue to the sequence disassembly plan. The process repeats to each part p , until all parts p' are added to the sequence disassembly plan. In each cycle, each part p under study becomes a constrained component to retrieve.

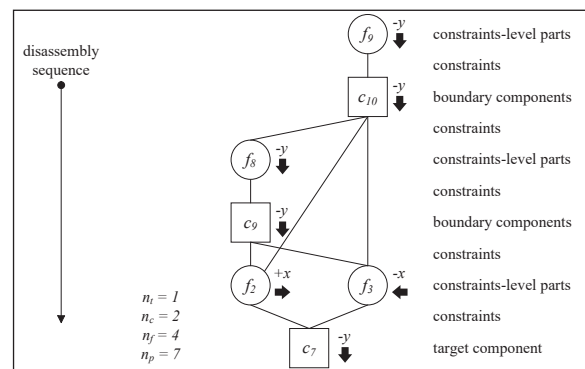


Fig 3: Single-target disassembly sequence plan graph for target component c_7 .

Instead of generating all possible paths for the disassembly sequence planning of a component target, expert rules can be used to find an optimized sequential disassembly plan that removes all parts, based upon motion, hosting, environmental and economic constraints [10]. Then the individual plans of all the parts to be removed are merged into one and the environmental/economic

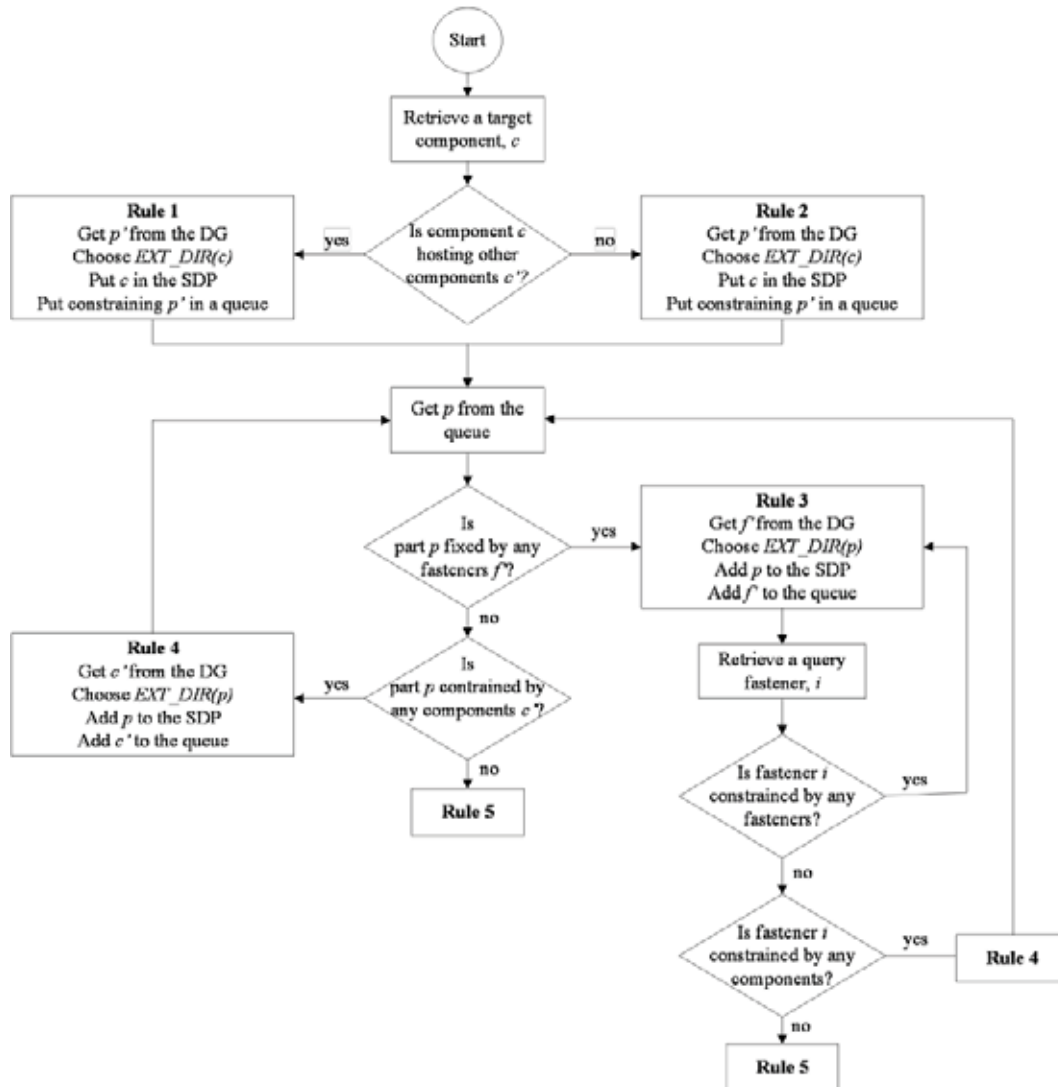


Fig. 4 : An approach for creating a Sequence Disassembly Planning for Buildings (SDPB).

performance of the whole process is reported. The approach in this study uses expert rules to improve solution quality, minimize graph complexity, and reduce searching time [9]. The rules use the *LC*, *HC*, *PC*, *EnvC* and *EC* matrices to choose part disassembly directions. The following are the expert rules which define the recursive selective disassembly planning process.

- Rule 1: The best disassembly direction for removing the target component t is the direction $EXTRACTION\_DIRECTION(c)$ which contains the most number of hosted components MF_t-HC in the MC_t direction.
- Rule 2: If the target component t is not hosting any other components, then the best disassembly direction for removing t is $EXTRACTION\_DIRECTION(c)$ for which the sum

of the environmental impacts or building cost of the blocking components is the lowest.

- Rule 3: All f' that physically constrain c must be removed before c .
- Rule 4: All c' that constrain p in $EXTRACTION\_DIRECTION(p)$ must be removed before p .
- Rule 5: The best direction for removing all p' is $EXTRACTION\_DIRECTION(p)$, unless the p' have pre-assigned disassembly directions.
- Rule 6: The least convenient disassembly direction option would be the one that overlaps their "working- space" with the ground.

In general, different rules can be used for different applications and they have the purpose of reducing the

complexity of the model. If the rules choose optimal directions, the approach finds optimal disassembly plans. However, as a drawback, if the rules choose optimized but not optimal directions, the approach finds optimized disassembly plans that may not be optimal.

The searching process first checks if the target component t is hosting secondary components. If so, the direction for the extraction in MC_t has to include must of them, according to the Rule 1. According to the Rule 2, if the target component t is not hosting any other components, then the best disassembly direction for removing t is the one in which the sum of the environmental impacts or building cost of the blocking components, is the lowest. Then, the searching process checks if component under study c_n is fixed by any fastener. If so, all the fasteners need to be disassembled before retrieving the component c_n , according to Rule 3. If a part p is not fixed or occluded by other parts, it can be disassembled and it can be placed in the final disassembly path, otherwise, all the fasteners and components in its way need to be disassembled first, according to Rule 4. The process retrieves the parts ($p'=c'$ or f) that constrain other parts under analysis in the given direction, puts the constraining parts in a queue, and moves one-part p_n at a time from the queue to the sequence disassembly plan. For the next iterations, new constraining parts of an old constraining part under analysis are added to the queue avoiding the duplication of any of them. The process repeats to each part p , until all parts p' are added to the sequence disassembly plan. In order to make the approach more realistic, it is possible to pre-assign disassembly directions to any part p that has to be performed in that way due to constructive procedures, according to Rule 5. Similarly, according to Rule 6, the overlapping of the working space path with the ground is the least practical option to disassemble a component. Expert rule 6 is a recursive rule that is used with all the other expert rules. Figure 4 shows a flowchart of the searching process. The selective disassembly planning method is iterative, since Rules 3 and 4 add new constraining parts to the queue under analysis. Part by part is analyzed until the entire disassembly planning is complete for a target component.

6. Conclusions and outlook

This paper establishes the reference framework of the key role that adaptive reuse of buildings has inside the circular economy value chain in construction. Also, this study describes the principles for improving the process of adaptive reuse with a technical approach, as well as the importance of disassembly planning inside this process. In the end, a novel single-target selective disassembly sequence planning method for buildings is developed as a contribution for solving the problem of adaptive reuse of the building stock.

During the process of adaptive reuse of an existing building, specific parts must be selectively disassembled for repair, reuse, recycle, or

refurbishment. Prior studies describe methods for removing single or multiple targets from a manufactured product. These studies have thoroughly considered solution quality, model complexity, and searching time. However, none of these prior studies have been applied to building disassembly or adaptive reuse. The goal of this study is to develop a new selective disassembly sequence planning method for retrieving target components from buildings. The new method is based on the disassembly sequence structure graph (DSSG) model theory for manufactured products. Also, this method involves an environmental-impact, building-cost, and rule-based analysis for finding efficient disassembly sequence plans.

The new method contains the set of parts that must be removed in order to remove the target parts. Aside from this, the method is able to improve the environmental-impact or the building-cost performance for the disassembly process depending on preferences. The method uses expert rules to choose parts, part order, and part disassembly directions, based upon physical constraints. The method was created to find practical, realistic, and physically feasible solutions for selective disassembly of buildings. The solutions remove parts in a practical order and with realistic part motions for the building components. The solutions remove obstructed parts in subassemblies. Even though the disassembly planning method developed in this study can be implemented in a generic way to any kind of building assemblages, finding repetitive patterns or repetitive subassemblies is an excellent way to reduce the complexity of the model and to make it more practical. It is obvious that due to the high standardization of certain types of residential and commercial buildings, it is possible to find the patterns of repetition of the subassemblies and then to segment and study them separately in order to simplify the complexity of the analysis. At the end, the objective is to find a generic solution for the set of repetitive elements.

As future research, the new method has to be validated through case studies. For multiple targets, the method presented in this study could be extended to create a disassembly sequence plan for each component, with their respective best individual direction.

More investigation related to the environmental impacts and building costs of selective disassembly, selective demolition, and building refurbishment is desirable, with the aim of making the results of this study more accurate and practical. Generating the initial constraint matrices in an automatic way, for instance by retrieving data and constraints directly from the BIM model or through point cloud processing has potential as well.

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Low Portland Cement Contents Concrete with High Early Age Strength and High Resistance to Sulfate Attack

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Abstract: The Portland cement component of concrete is responsible for up to 90% of concrete's embodied energy and greenhouse gas emissions. Portland cement contents of concrete typically range from 300 to 450 kg/m³. A low Portland cement content concrete (LPCC) was developed using a mixture of supplementary cementitious materials (SCMs) to optimize particle packing. Fly ash was the main constituent of the SCMs, but slag, metakaolin and limestone powders were also used to optimize both the early strength and later-age properties. The results showed that a concrete mixture with only 70 kg/m³ Portland cement content had 1, 7 and 28-day age compressive strengths of 10, 43, and 52 MPa, respectively. Concretes made with Portland cement contents of only 186 kg/m³, 116 kg/m³ and 70 kg/m³ had excellent resistance to sulfate attack both at 23 °C and 5 °C.

Keywords: Low Portland Cement Contents Concrete, Limestone Powders, High Early-Age Strength, High Resistance of Sulfate Attack, Supplementary Cementitious Materials (SCMs)

1. Introduction

High-volume SCMs concretes (or low Portland cement concretes) have been more and more used in construction in recent years. Usually, the volumes of fly ash are between (40-60) % of powders in concrete and the contents of the high-volume SCMs mixtures containing slag could be more than 70% of total binder. But the low early-strength and the delayed setting time are still obstacles to its application.

The properties of concretes which have SCMs contents from (25-70) % of total binder are investigated here. To improve the early-age strength, fine limestone powders, high range water reducer admixture with strength-accelerating effect, and the synergy from mixed SCMs were combined employing.

2. Experiments

2.1 Constituent Materials

- **Cement (GU):** Holcim (now CRH) GU, Mississauga, ON;
- **Fly Ash (FA):** Class F, Sundance, Canada
- **Slag (SL):** Holcim Slag, Mississauga, ON;
- **Metakaolin (MK):** Whitemud Resources, Saskatchewan, Canada
- **Limestone powder (LM):** Betocarb®6-PT, Omya Canada
- **Polycarboxylate high range water reducer admixture (SP)**
- **Water (W)**—Tap water

2.2 Mixture Proportions

The contents of the Portland cement, SCMs, limestone powders, as well as the high range water reducer admixture of the concrete mixtures used for compressive strength tests are shown in Table 1. The nominal contents of the sand and the coarse aggregates for all mixtures were 680 kg/m³ and 1080 kg/m³, respectively. The ratio of water to powders was 0.30 and the water content was 140 kg/m³ for all the mixtures.

Table 1 Mixture Proportions of Powders Used in Concretes for Compressive Strength Tests (kg/m³)

Mix	GU	SL	FA	MK	LM	SP
0	465 100%P	0	0	0	0	5.81 1.25%P
1	279 60%P	0	116 25%P	0	70 15%P	11.6 2.5%P
2	186 40%P	19 4%P	171 36%P	19 4%P	70 15%P	11.6 2.5%P
3	116 25%P	28 6%P	223 48%P	28 6%P	70 15%P	5.8 1.25%P
4	70 15%P	116 25%P	186 40%P	23 5%P	70 15%P	4.65 1.0%P

* P is the sum of all powders, including GU, SL, FA, MK, and LM

The ASTM C1012 mortar mixtures for measuring sulfate resistance had the same constituents and proportions of powders as in Table 1, except that the ratio of the sand to total powder was 2.75 and the ratio of water to total powder was 0.485. As well, No SP was used in the mortar mixtures (Table 2).

Table 2 Mixture Proportions for Sulfate Resistance Tests

Mix	GU	SL	FA	MK	LM
0	100%P	0	0	0	0
1	60%P	0	25%P	0	15%P
2	35%P	4%P	42%P	4%P	15%P
3	25%P	6%P	48%P	6%P	15%P
4	15%P	25%P	40%P	5%P	15%P

2.3 Test Methods

The procedure used for concrete mixing, including procedures for both workability tests and casting specimens followed ASTM C 192. An 18L flat pan concrete mixer was employed. 100x200mm cylinders were cast for compressive strength. Casting and curing procedures for cylinders followed ASTM C192. The cylinders were demoulded after 24 hours and stored in a

moist room at 23 ± 2 °C and until tested at the ages of 1d, 7d and 28d. The remaining cylinders were kept in the lab at about 23 °C & 50%R.H after 28 days.

The sulfate-resistance experiments followed ASTM C 1012.

3. Results and Discussion

3.1 Compressive Strength

The concretes had high 1-day compressive strengths and stable development of compressive strengths with increasing age (Table 3). All of the 7-day strengths were more than 80% of their 28-day compressive strengths. The strengths continued to rise after 28 days.

The concrete with a Portland cement content of 279 kg/m³ attained a 1-day strength of 40.1 MPa and a 28-day strength of 66.7 MPa (Mix 1). Even the concrete with only 70 kg/m³ cement content had a 1-day strength of 9.9 MPa and 50.2 MPa at 28 days.

Table 3 Compressive Strengths of Concretes (MPa)

Mix	f _{1d}	f _{7d}	f _{28d}	f _{56d}
0	75.3	82.7	92.2	96.5
1	40.1	57.5	66.7	92.2
2	25.1	55.1	64.8	77.6
4	19.5	51.9	63.2	68.2
5	9.9	43.0	50.2	53.3

3.2 Sulfate Attack Resistance

The resistance to sulfate attack of CSA Type GU and Portland cement concrete is poor, with or without limestone powders. However, partial replacement with SCMs can improve resistance to sulfate attack for both Portland cement concrete and concrete with limestone powders. [1]. In CSA A3001, a maximum expansion limit of 0.10% at 12-months is required to demonstrate high sulfate resistance. Measurements were not taken at 12 months, but 1-month measurements are provided

in Table 4.

3.2.1 Tests at 23°C

As expected, the expansion of the mortar bars of Portland cement Mix 0 (Table 4) was much higher than the 0.10% expansion criteria at 18-months [2]. All the mixtures with SCMs effectively decreased the expansion to below the 0.10% criteria even with 15% limestone powder.

Table 4 Average ASTM C1012 length change in Na₂SO₄ solution at 23 °C (%)

	Mix 0	Mix 1	Mix 2	Mix 4	Mix 5
Week1	0.0096	0.0038	0.0023	0.0021	0.0008
Week2	0.0145	0.0097	0.0016	0.0008	0.0009
Week4	0.0194	0.0126	0.0017	0.0018	-0.0004
Week5	0.0156	0.0146	-0.0047	-0.0049	0.0063
Month18	1.282	0.0342	0.0081	0.0008	-0.002

3.2.2 Tests at 5 °C

As expected, the Portland cement Mix 0 (Table 5) expanded higher than the 0.10% expansion limit [2] and suffered higher mass loss in the cold sulfate solutions after 18 months (Fig.1). Although the expansion of Mix 1 was below the expansion limit [2], the samples lost mass and were visually damaged after 18 months exposure (Fig.1). However, the mixtures Mix 2, Mix 3 and Mix 4 (Table 5) were in excellent visual condition and did not expand. It can be concluded mixtures with 40% or less of Portland cement have good resistance to sulfate attack at 5 °C regardless of the presence of up to 15% limestone powder.

Table 5 Average modified ASTM C1012 expansion in Na₂SO₄ solution at 5 °C (%)

	Mix 0	Mix 1	Mix 2	Mix 4	Mix 5
Week1	-0.01	-0.0152	-0.0181	-0.0179	-0.0169
Week2	-0.0049	-0.0109	-0.0145	-0.0148	-0.0181
Week4	-0.0033	-0.0087	-0.0124	-0.0090	-0.0163
Week5	-0.0016	-0.0007	-0.0085	-0.0090	-0.0211
Month18	0.2855	0.017	0.0009	-0.0096	-0.0145



Mix 0

Mix 1

Fig. 1 Visual Damage to Mortar Bars in Sulfate Solution at 5 °C for 18 Months

4. Conclusions

The concrete with Portland cement contents no more than 40% of the total powders have high compressive strengths both at early ages and later ages.

Mortar mixtures with cement contents no more than 40% of the powders also have good resistance to sulfate attack both at 23 °C and 5 °C.

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New and sustainable Civil Engineering infrastructures from geopolymer concrete and GFRP bars

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Abstract:

Fibre-Reinforced Polymer (FRP) composites reinforcing bars have gained considerable worldwide interest as internal reinforcement for concrete structures to address the corrosion problem in steel reinforcement. At the same time, the use of geopolymer concrete is currently attracting increasingly widespread attention because its manufacture does not directly create CO₂ emissions. Geopolymer concrete is considered as a “green cement” and has great potential to be used as a building material. The combination of these new and emerging construction materials is anticipated to produce next generation of reinforced concrete (RC) structures with increased durability and substantially reduced embodied carbon compared to conventional steel reinforced Ordinary Portland cement (OPC)-based concrete while providing requisite of strength and structural integrity.

This paper presents the results of the on-going research and developments on the structural behaviour of geopolymer concrete structures reinforced with glass-fibre-reinforced polymer (GFRP) composites bar to demonstrate the construction and performance capacity of this new construction system. The results of the extensive experimental and theoretical investigations showed that the GFRP-geopolymer concrete bond was higher than that of GFRP-OPC concrete bond, suggesting a full composite action can be achieved between geopolymer concrete and GFRP bars. For a similar amount of longitudinal reinforcement, the GFRP-geopolymer concrete beam yielded higher flexural strength but inferior serviceability performance than that of steel-reinforced geopolymer concrete beams. Moreover, geopolymer concrete columns reinforced with GFRP bars yielded relatively superior compression strength than OPC-based concrete columns due to the better compatibility of GFRP bars with geopolymer concrete compared with OPC concrete, owing to the higher elastic modulus of the former concrete compared to the latter concrete. Based on these findings, it can be concluded that geopolymer concrete reinforced with GFRP bars is a doable application and could begin to be employed in the construction of durable and sustainable Civil Engineering infrastructure.

Keywords:

Geopolymer concrete, GFRP bars, bond, beams, columns (3-5 keywords).

1. Introduction

The recent advances in fibre-reinforced polymer (FRP) composite technology have resulted in the extension of its application in the construction industry, particularly as internal reinforcement for concrete structures, primarily to enhance the durability and to prolong the serviceability of these structures. The corrosion-induced durability problems could be eliminated if chemically inert or non-metallic reinforcement like fibre-reinforced polymer (FRP) bars could replace steel bars as the primary reinforcement within concrete structures [1, 2]. Furthermore, FRP bars seems to be the best option when low electric conductivity and electromagnetic neutrality are sought or lightweight is an important design factor. They also have high tensile strength (2-3 times that of steel), high strength-to-weight and stiffness-to-weight ratios, high fatigue resistance, and good thermal insulation, with the added benefits of ease in fabrication, transportation, and handling and the potential for real-time monitoring [3, 4]. In comparison with steel reinforcement, however, FRP reinforcement have

lower elastic modulus, shear strength, and compressive strength. Furthermore, unlike steel, they behave linearly-elastic up to failure and lack ductility [5].

The apparent higher initial expenditures, specifically the material costs, of FRP bars over steel bars is one of the major reasons for its slow uptake in the construction industry. Yet, a direct comparison on the unit price basis may not be appropriate. The life cycle cost analysis performed by Najm [6] on concrete bridge decks reinforced with FRP bars highly recommended the use of FRP reinforcement in corrosive environments. According to Nkurunziza et al. [7], FRP bars are more economical and more adequate than epoxy-coated or galvanized steel when used for concrete structures under corrosive environments. The use of FRP bars as reinforcement in concrete structures is also particularly suitable when transportation cost increase significantly with the weight of the materials. Furthermore, the inconvenience of retrofitting damaged members and the costly repair and maintenance are the other

economic factors that must be considered in adopting FRP bars [8].

Research and development on FRP-reinforced concrete (FRP-RC) had become tantamount that several countries had developed their own design guidelines (JSCE-1997 [9] in Japan; ISIS 3(2)-01 [10], CAN/CSA S6-14 [11] and CAN/CSA S806-12 [12] in Canada; CNR-DT 203/06 [13] in Italy and fib Bulletin 40 [14] in Europe; and ACI 440.1R-15 [15] in the USA). Most of these codes were derived from the provisions for the traditional RC members, with several modifications to account for the different physical and mechanical properties between FRP and steel bars.

Geopolymer concrete, on the other hand, is a viable alternative to the traditional Ordinary Portland Cement (OPC)-based concrete for the development of greener and more sustainable structures because, instead of cement paste, the geopolymer binder can be manufactured using by-product materials that are rich in silica and alumina, such as fly ash and blast furnace slag [16]. Davidovits [17] coined the term “geopolymer” since the chemical reaction that takes place between the source materials and the activating alkaline liquid is a polymerisation process. The geopolymer concrete production have 80-90% lower CO₂ emission compared to the process of manufacturing OPC-based concrete [18]. The production of geopolymer can also minimise the landfill necessary for fly ash that is reportedly abundant worldwide, but limitedly utilised worldwide; however, its utilisation is limited. Furthermore, the geopolymer binder can immobilise approximately 90% of heavy metals within its matrices [19, 20].

Geopolymer binders exhibited superior mechanical properties to those of OPC binders [21, 22]. Furthermore, geopolymer concrete have strength, stiffness, and other mechanical properties that are comparable and, most of the time, superior to that of OPC-based concrete [23-25]. The other desirable characteristics of geopolymer concrete include rapid development of mechanical strength, fire resistance, dimensional stability, acid resistance, excellent adherence to aggregates and reinforcements, and have lower material cost, approximately 10-30% lower than that of OPC concrete [18]. It has very little drying shrinkage and creep and showed excellent resistance to sodium sulphate [26]. With the highly desirable structural properties of geopolymer concrete, a significant cost savings in many structural members is expected [27].

The adoption of GFRP bars in place of steel bars as the primary reinforcement for concrete structures is now commonly practiced to enhance the durability and prolong the serviceability of the structures while the use of geopolymer concrete, instead of cement-based concrete, is particularly suitable for the fabrication of environmentally-friendly concrete

structures. With the stated advantageous properties of GFRP bars and geopolymer concrete, including their successful applications in the construction of various civil infrastructures, combining them would offer a promising technology in building new structures with high durability and high sustainability and with adequate strength and structural integrity. The poor understanding of the overall behaviour and the lack of designers' experience with GFRP-reinforced geopolymer concrete (GG) system, however, may place this new and innovative technology at a disadvantage when compared against the existing GFRP-reinforced ordinary concrete (GO) and steel-reinforced geopolymer concrete (SG) systems. A logical step, therefore, is to investigate the important aspects of their structural behaviour such as the GFRP-geopolymer concrete bond, the flexural behaviour of GG beams, and the compression performance of GG columns. However, limited scientific research had been undertaken to substantiate the benefit of using GG system. This was the main motivation for this study. Hence, this study was designed to assess the suitability and structural behaviour of GG system and extend the understanding into the critical problems associated with their application, thereby filling the knowledge gap that currently exist in civil engineering.

2. Material Properties

High modulus (HM) pultruded GFRP bars (Grade III, CSA S807-10 [28]) of varying nominal diameters (ϕ_r) were considered in the study (Figure 1). The bars were made up E-glass fibres impregnated with a modified vinyl ester resin. The surface of the bars were coated with silica sand to enhance its bonding properties. The nominal cross sectional area (A_b), guaranteed tensile strength (f_{ps}), modulus of elasticity (E_f), ultimate elongation (ϵ_f), and fibre content by mass (M) of the bars as specified by the manufacturer [29] are summarised in Table 1.

On the other hand, a ready-mix geopolymer concrete (Figure 2) with a commercial mix design, supplied locally in Toowoomba, Australia, was used in this study. It is composed of a blend of fly ash (FA) and ground granulated blast furnace slags (GGBFS), gravel, sand and water with a proprietary chemical hardener solution. The main feature of this type of geopolymer concrete is that it can be delivered and cured on-site under ambient conditions. The 28-day compressive strength (f'_c) and elastic modulus (E_c) were determined in accordance with ASTM C39/C39M and were summarised in Table 2.

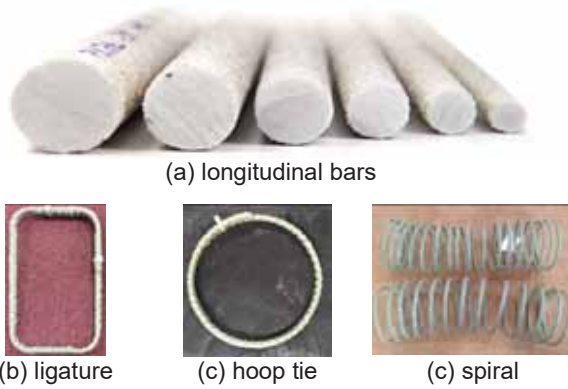


Fig 1: Glass-fibre-reinforced polymer (GFRP) reinforcement



Fig 2: Geopolymer Concrete

Table 1: Properties of GFRP bars

$\varnothing_f^*$ (mm)	A_f (mm ²)	f_{ps}^{**} (MPa)	E_f (GPa)	ε_f (%)	M (%)
9.5 (#3)	82	1029	50	2.06	77.6
12.7 (#4)	129	1312	65.6 ± 2.5	2.00	84.1
15.9 (#5)	199	1184	62.6 ± 2.5	1.89	83.9
19.0 (#6)	284	1105	63.7 ± 2.5	1.71	84.0

*Numbers inside the () are the manufacturer's bar designation

**Guaranteed tensile strength: Average value – 3x standard deviation

Table 2: 28-day compressive strength and elastic modulus of geopolymer concrete

Test	f'_c (MPa)	E_c (GPa)
Direct pullout test	33	29
Four-point static bending test	38	33
Uniaxial compression test	38	33

3. Test Methods

3.1 Direct Pullout Test

The effects of the nominal diameter of GFRP bars ($\varnothing_f$) and embedment length (l_d) were investigated. For comparison purposes, deformed steel bars with a nominal diameter ($\varnothing_s$) of 16.0 mm and a yield strength (f_y) of 500 MPa was considered. For each type of specimen, three replicates were prepared yielding 27 GFRP-geopolymer (GG) and 18 steel-geopolymer (SG) bond-slip specimens. The

specimens were labeled as follows: specimen type-bar diameter-embedment length. For example, GG-12.7-5 $\varnothing_f$ represents the specimen with a 12.7 mm GFRP bar embedded five times the bar diameter in the geopolymer concrete.

The ACI 440.3R-04 direct pullout test method was used as a reference to examine the bond behaviour of GFRP bars in geopolymer concrete. Figure 3 presents the schematic diagram and the actual test setup. The absolute slip of the GFRP bar in the geopolymer concrete was measured using a Linear Variable Differential Transducer (LVDT) placed on top of the unloaded end of the bar. System 5000 data logger was used to capture and record the pullout load and the free end-slip displacement of each specimen.

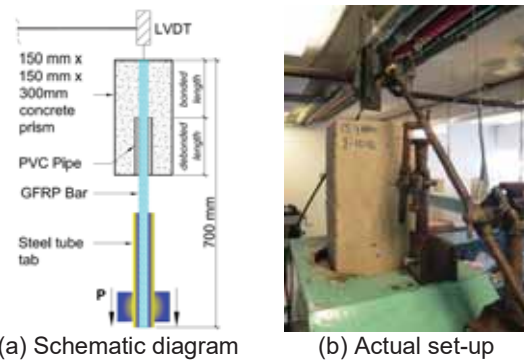


Fig 3: Direct pullout test

3.2 Four-point Static Bending Test

Five (5) GFRP-reinforced geopolymer concrete (GG) beams were cast and tested up to failure. Each beam has a total length (L_t), width (b), and total depth (h) of 3100 mm, 200 mm, and 300 mm, respectively. The test parameters include the bottom longitudinal reinforcement ratio (ρ_f) and the nominal diameter of the tensile reinforcement ($\varnothing_f$). The control specimen, steel-reinforced geopolymer concrete (SG) beam, had 3-16.0 mm deformed steel bars at the bottom. All the tested beams were longitudinally reinforced with 2-12.7 mm GFRP bars at the top and transversely reinforced with 9.5 mm GFRP stirrups spaced at 100 mm on-centre. Figure 4 shows the typical cross-sectional configuration of each beam. The specimens were labeled based on their type and tensile reinforcement. For example, the specimen identified as GG-2-19.0 mm embodies the geopolymer concrete beam reinforced with two (2) 19.0 mm GFRP bars at the bottom. The parameters ρ_f and ρ_{fb} (balanced reinforcement ratio) were computed in accordance with CSA S806-12 [12] recommendations.

Figure 6 shows the schematic diagram and actual test setup of the four-point static bending test. Two concentrated loads, 400 mm apart, were applied at midspan of the beam with a support-to-support distance (L) of 2600 mm, yielding a shear span (a) of 1100 mm on both sides. The load was applied

through the spreader I-beam at a displacement rate of 3 mm/min using the 200 tonne capacity hydraulic jack. The beams were instrumented with a Laser Displacement Sensor (LDS), at the bottom midspan to monitor deflections, and strain gauges attached on the critical portions of the beam (e.g. top surface of the geopolymer concrete, top surface of compression bars, and bottom surface of the tensile reinforcement). The applied loads, midspan deflections, and strains were recorded and capture using the System 5000 Data Logger.

3.3 Uniaxial Compression Test

Six 250 mm diameter and 1000 mm high geopolymer concrete columns reinforced with 6-15.9 mm HM GFRP bars (approximately 1.7% of the gross section area of the column) were prepared and tested. The first column, without transverse reinforcement, served as the control specimen. The second, third, and fourth columns were transversely reinforced with 9.5 mm GFRP circular hoops spaced at 50 mm, 100 mm, and 200 mm on-centres, respectively, while the fifth and sixth columns were laterally reinforced with 9.5 mm GFRP spirals spaced at 50 mm and 100 mm on-centres. Figure 5 presents the typical cross-sectional configuration of each column. The columns were identified based on the lateral reinforcement type and spacing. For example, the specimen identified as GG-S-50 stands for the geopolymer concrete column transversely reinforced with spirals spaced at 50 mm on-centre.

Figure 7 presents the schematic diagram and actual setup of the uniaxial compression test employed in the study. The axial loads were applied in displacement control mode using a hydraulic jack with 200 tonne capacity. The magnitude of the applied loads was measured using a load cell while the corresponding deformations were measured using a string pot. Three equally spaced strain gauges were mounted at mid-height of longitudinal bars. In addition, another three strain gauges were attached on the geopolymer concrete surface, aligned with those bonded at the bars. Four strain gauges set 90° apart were also used to capture the strains in the transverse reinforcement. The applied axial loads, axial deformation, and axial and hoop strains were recorded using the System 5000 data logger attached to the machine.

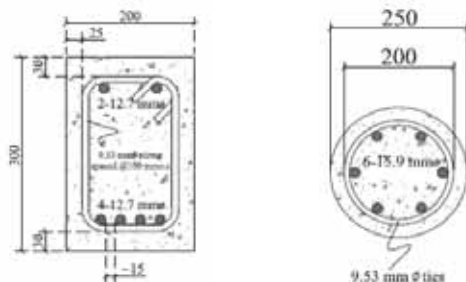
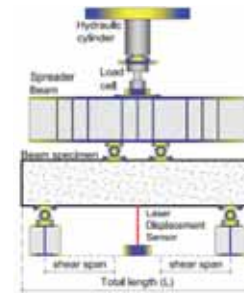


Fig 4: Typical cross-sectional configuration of the tested beams (all dimensions are in mm)



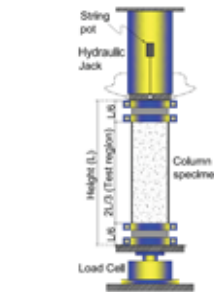
(a) Schematic diagram

Fig 5: Typical cross-sectional configuration of the tested columns (all dimensions are in mm)



(b) Actual setup

Fig 6: Four-point static bending test



(a) Schematic diagram



(b) Actual setup

Fig 7: Uniaxial compression test

4. Results and discussions

4.1 GFRP-geopolymer concrete bond

All GG and SG bond-slip specimens with 5 ϕ_f embedment length failed due to pullout of GFRP and steel bars from geopolymer concrete (Figure 8a), respectively. On the other hand, GG specimens with embedment lengths of 10 ϕ_f and 15 ϕ_f failed due to splitting of geopolymer concrete (Figure 8b) while SG specimens with the same bonded lengths exhibited rupture of steel bars (Figure 8c). In general, as the bar diameter and embedment length increase, the severity of geopolymer concrete splitting increases.

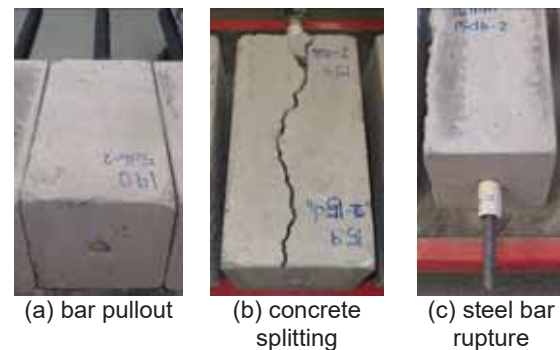


Fig 8: Failure mode of bond-slip specimens.

The average failure load (P_p) and bond stress (σ_p), calculated from Eq. 1, were summarised in Table 3.

$$\sigma_p = \frac{P_p}{\pi \phi_f l_d} \quad (1)$$

The relationship between σ_p and l_d is shown in Figure 9. From the figure, irrespective of embedment length, the increase in bar diameter causes the peak average bond stress to decrease. This finding corroborates with experiment results reported by Arias et al. [30], and Tighiouart et al. [31] for the sand-coated GFRP bars embedded in ordinary concrete. The nonlinear distribution of stresses (maximum in the loaded end and minimum in the unloaded end) is more dominant in bars with larger diameter that leads to lower bond strength. In addition, the GFRP bars with larger diameter experienced higher Poisson's ratio effect that resulted in a lower bond between the bars and the concrete [32].

Increase in embedment length leads to a weaker bond between the bar and geopolymer concrete regardless of bar diameter, which was consistent with the previous findings [31, 33] for GFRP-concrete system. Tighiouart et al. [31] explained that as the embedment length increases, the applied load reached the tensile strength of the rebar and the average bond strength diminishes. They also added that this behaviour was a consequence of the nonlinear stress distribution along the bonded length, which was more pronounced in bars with longer embedment. Tang et al. [34] also added that that an increase in the embedment length leads to an increase in the perimeter area and thus, a decrease in bond strength.

The average bond stresses calculated in GG-15.9 specimens were comparable to that of the SG-16.0 specimens, suggesting that the mechanical interlock and friction forces coming from the sand-coating are enough to adequately anchor the GFRP bars to geopolymer concrete. It can be deduced, therefore, that the sand-coated GFRP bar is a viable alternative to steel as internal reinforcement for geopolymer concrete structures.

Table 4 shows the comparison between the average σ_b/f'_c and corresponding standard deviation (STD) of GFRP-geopolymer concrete and GFRP-concrete bond-slip specimens. The considered specimens failed due to bar pullout and have nominal bar diameter, embedment length, and concrete compressive ranging from 8.5-19.1 mm, $4\phi_f$ – $10\phi_f$, and 15-49 MPa, respectively. Based on the table, the GFRP-geopolymer concrete system have better bond performance than the GFRP-concrete system, suggesting the viability of the proposed system for structural applications.

Table 3. Failure load, average bond stress, and failure of GG and SG specimens

Specimen	P (kN)	σ_b (MPa)	Failure mode*
GG-12.7-5 ϕ_f	61	24.0	BP
GG-12.7-10 ϕ_f	117	23.1	BP
GG-12.7-15 ϕ_f	120	15.8	CS
GG-15.9-5 ϕ_f	86	21.4	BP
GG-15.9-10 ϕ_f	144	18.1	CS
GG-15.9-15 ϕ_f	163	13.6	CS
GG-19.0-5 ϕ_f	116	19.4	BP
GG-19.0-10 ϕ_f	159	13.3	CS
GG-19.0-15 ϕ_f	139	7.8	CS
SG-16.0-5 ϕ_f	94	23.4	BP
SG-16.0-10 ϕ_f	119	14.8	BR
SG-16.0-15 ϕ_f	126	10.5	BR

*BP = bar pullout; CS = concrete splitting; BR = bar rupture

Table 4. Comparison between GFRP-geopolymer concrete and GFRP-concrete bond.

Author	σ_b/f'_c (MPa)	STD (MPa)
Current Study	0.67	0.06
Achillides & Pilakoutas [32]	0.33	0.10
Arias et al. [30]	0.39	0.08
Belarbi & Wang [35]	0.39	0.04
Lee et al. [36]	0.23	0.03
Tighiouart et al. [31]	0.25	0.07

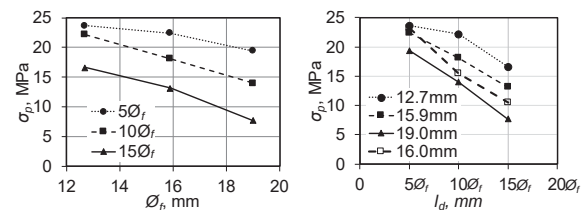


Fig 9: σ_p - ϕ_f relationship Fig 10: σ_p - l_d relationship

4.2 GFRP-geopolymer concrete beam

As expected, the over-reinforced geopolymer concrete beams with GFRP bars (GG- beams) failed in flexure through the crushing of the geopolymer concrete in the compression zone (Figure 11) while the under-reinforced geopolymer concrete beam with steel bars (SG-3-16.0) failed in flexure but was induced by the yielding of the steel bars.

Figure 12 shows the relationships between the bending-moment (M) and the midspan deflection (Δ) of the tested beams. Generally, three ascending linear segments with a decreasing slope, followed by an unloading curve, represent the M - Δ of GG- beams. This behaviour was different from the two-segment curve reported in previous studies for FRP-reinforced concrete [37, 38]. The first linear segment represents the uncracked stage that was similar for all the tested

beams. At this stage, the geopolymer concrete governed predominantly the behaviour of the beam. When the applied load exceeded the average cracking moment (M_{cr}) of 10.9 kNm, vertical cracks began to form at the bottom midspan. This marked the beginning of the cracked stage embodied by another linear segment with a reduced slope. The slope increases with the reinforcement ratio as was also reported in the previous works. [38-40]. The third linear segment represent the crushed stage, wherein the geopolymer concrete reached its maximum compressive strain; however, the beam continued to sustain further loads owing to bending-moment resistance provided by the stirrup-confined geopolymer concrete and the unruptured tensile GFRP bars. The load application was halted prior to reaching the capacity of the load applicator to avoid any mishaps. Finally, the unloading segment represented the gradual removal of the applied loads. This behaviour tends to indicate the elastic characteristic of the beams even after the geopolymer concrete crushing failure.

SG-3-16.0 yielded $M-\Delta$ composed of two consecutive linear segments tailed by a plateau segment and an unloading segment, respectively. The initial linear segment was similar to that of GG-3-15.9. At second linear stage, however, SG-3-16.0 produced higher stiffness compared to GG-3-15.9, which showed that the former have better serviceability performance compared to the latter beam. This can be anticipated since the elastic modulus of steel bars is more than three (3) times larger than that of GFRP bars.



Figure 11: Typical failure mode of GG-beams

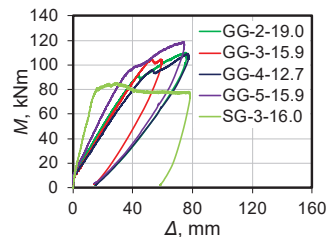


Figure 12: $M-\Delta$ relationship of the tested beams

The bending-moment at concrete crushing failure (M_{cc}) and the peak bending-moment after concrete crushing (M_u) of GG- beams are summarised in Table 5. Based on the table, GG- beams exhibited analogous M_{cc} with an average value of 98 kNm. GG-5-15.9 produced M_u (19 kNm) that was just 13% higher than GG-3-15.9 (105 kNm), which tend to support the earlier findings by Kassem et al. [7] who found that by doubling ρ_f , the capacity of the beam increased by just 16 %. In general, these results tend to indicate that the bending-moment capacity of GG-beams was not directly influenced by the bar diameter and reinforcement ratio.

SG-3-16.0, on the other hand, produced a bending-moment capacity at steel yielding (M_{sy}) equivalent to 85 kNm, which was 15 % lower compared to M_{cc} of GG- beams. At the final stage of loading, the M_u of SG-3-16.0 was equal 74 kNm for, which was 42% lower compared to M_u of GG-3-15.9. These outputs showed the superiority of GFRP bars over the steel bars in terms of load-carrying capacity.

This study utilised Bichoff et al.'s [41] criterion to determine the deflection at service condition (Δ_s), which is defined as the deflection at $0.3M_u$. By referring to Table 4, comparable Δ_s were obtained from GG-2-19.0, GG-3-15.9, and GG-4-12.7, having an average value of 10.8 mm, suggesting that the bar diameter have no significant influence on the serviceability performance of GG- beams. On the contrary, the serviceability performance tend to get better by increasing ρ_f . GG-5-15.9 (8.0) yielded a lower Δ_s compared to GG- beams with lower ρ_f . As expected, SG-3-16.0 (3.7 mm) produced lower Δ_s compared to GG- beams.

Table 6 presents the average normalised bending moment capacity ($M_u/f_c b d^2$) of GG- beams and that of the published results on GFRP-reinforced ordinary concrete (GO) beams with nearly similar dimensions and configurations as the tested GG- beams. From Table 7, it can be inferred that GG- beams showed better strength compared to GO beams. Additional experiment works, however, are recommended to verify this observation.

Table 5: Bending-moment capacity and deflection at service of the tested beams

Specimen	ρ_f (%)	ρ_{fb} (%)	M_{cc} (kNm)	M_u (kNm)	Δ_s , mm
GG-2-19.0	1.13	0.12	91	110	8.8
GG-3-15.9	1.18	0.11	105	105	12.3
GG-4-12.7	1.00	0.09	96	109	11.5
GG-5-15.9	2.12	0.11	99	119	8.0
SG-3-16.0	1.19	2.59	85*	74	3.7

* M_{sy} = bending-moment capacity at steel yielding

Table 6: Average normalised bending moment capacity of GG- beams and GFRP-reinforced ordinary concrete (GO) beams

Reference	Beam	$M_u/f_c b d^2$	STD
Current Study	GG- beams	51	2.5
Kassem et al. [38]	G1-6, G1-8	45	-
Toutanji & Deng [42]	GB3-1, GB3-2	46	-
Benmokrane et al. [43]	ISO1, ISO2	35	-
Benmokrane et al. [44]	ISO30-2	36	-

4.3 GFRP-geopolymer concrete column

Fig. 13 shows the typical post-failure configuration of the tested columns. A well-formed cone on both ends and global buckling of longitudinal GFRP bars (Figure

13a) transpired in the unconfined and poorly confined columns (GG-00 and GG-C-200, respectively). With the provision of adequate lateral reinforcement, the failure mode changed. The failure configuration of the columns confined by hoops (GG-H-50 and GG-H-100) and spirals (GG-S-50 and GG-S-100), presented in Figures b and c, respectively, was typified by the sequential occurrence of the following: 1) geopolymer concrete crushing and local buckling of GFRP bars, 2) concrete cover spalling, and 3) lap splice failure of circular hoops or rupture of spirals. In general, the column with closely spaced lateral reinforcement exhibited less brittle failure compared to those with largely spaced lateral reinforcement.

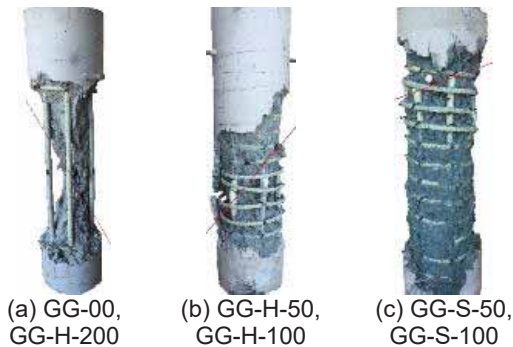


Fig 13: Typical failure mode of the tested columns

Figure 14 presents the relationships between the axial load (P_c) and the axial deformation (Δ_c) of the tested columns. The P_c - Δ_c curve of GG-00 was composed of a linear ascending segment up until the peak load (P_{cc}). P_{cc} represents the gross capacity of the geopolymer concrete column or the capacity of the column before concrete cover spalling.

The P_c - Δ_c curves of confined columns can be subdivided into three segments. The first segment was comparable to that of GG-00 because the geopolymer concrete predominantly governed the behaviour of the column. A short nonlinear segment transpired prior to reaching the P_{cc} of each column, owing to concrete crushing and cracking followed by the formation of vertical hairline cracks on the concrete surface. At this stage, the passive confinement of the GFRP transverse reinforcement was activated. Right after exceeding P_{cc} , the concrete cover began to spall and a short descending segment transpired, which corresponds to the second stage response of the columns. The columns continued to carry additional loads due to the confined concrete core. This behaviour was the third stage response column, which was embodied by either an ascending line or a descending line, depending on the spacing of transverse reinforcements. A second peak load P_{cu} was recorded and this represents the maximum load capacity of the confined geopolymer concrete core. In general, the spiral-confined columns exhibited higher ductility strength compared to their counterpart hoop-confined columns due to continuous nature of the

spiral that effectively distributed the lateral confining pressures around and along the height of the column.

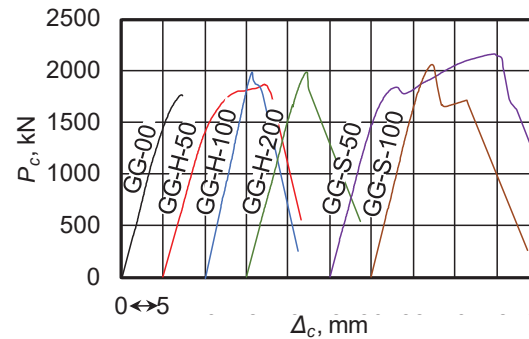


Fig 14: P_c - Δ_c of the tested columns

Table 7 summarises the P_{cc} and P_{cu} of the tested columns. The P_{cc} of GG-00 was 1772 kN, which translates to a strength capacity of 34 MPa or 0.90 times the f'_c of the geopolymer concrete cylinders used in the test. This value was higher than the commonly adopted ratio of 0.85 for estimating the theoretical capacity of the column. This could be due to the higher elastic modulus of geopolymer concrete that allowed better compatibility in GG system compared to GO. The use of transverse reinforcement, generally, enhanced the load-bearing capacity. The P_{cc} of GG-H-50, GG-H-100, GG-H-200, GG-S-50, and GG-S-100, on the other hand, were 1 %, 12 %, 12 %, 4 %, and 16 % higher than that of GG-00, respectively. This enhancement could be attributed to the activation of the lateral confinement of the transverse reinforcement right after exceeding a load level approximately equivalent to GG-00's P_{cc} .

Among the tested columns, only GG-H-50, GG-H-100, GG-S-50, and GG-S-100 yielded P_{cu} equivalent to 1872 kN, 1763 kN, 2160 kN, and 1691 kN, respectively, which were 105 %, 89 %, 118 % and 82 % of their P_{cc} , respectively. The well-confined columns (GG-H-50 and GG-S-50) yielded P_{cu} that were higher than their P_{cc} . The spiral-confined columns produced higher P_{cc} and P_{cu} compared to their counterpart circular tie-reinforced columns.

Table 7 also summarises the compression contribution of GFRP bars (P_f) at P_{cc} load level. The P_f of GG-00 was approximately 7% of the P_{cc} of GG-00 while those with lateral ties obtained P_f ranging from 7 % to 10% of their corresponding P_{cc} . These results suggested that the adopted longitudinal GFRP bars have notable compression contribution.

The performance of the tested columns was compared to GO columns in terms of their average normalised strength, which was calculated as the difference between P_{cc} and P_f divided by the concrete strength (f'_c) and the gross area of the column (A_g). It can be seen from Table 8 that the strength of GG columns were higher than that of GO columns.

Interestingly, this finding tends to support the authors' earlier claim that GFRP bars have better compatibility with geopolymer concrete compared with OPC concrete, owing to the higher elastic modulus of the former concrete compared to the latter concrete.

Table 7: The load capacity of the testes column specimens

Specimen	P_{cc} , kN	P_{cu} , kN	P_f , kN
GG-00	1772	-	123
GG-H-50	1791	1872	188
GG-H-100	1981	1763	133
GG-H-200	1988	-	134
GG-S-50	1838	2160	158
GG-S-100	2063	1691	147

Table 8: Normalised strength of GG and GO columns

Author	Type	$\frac{P_{cc} - P_{fg}}{f'_c A_g}$	STD
Current Study	Hoop	94.7	7.6
Mohammed et al.	Hoop	87.1	2.1
Current Study	Spiral	96.4	-
Afifi et al.	Spiral	88.6	1.5

5. Conclusions and outlook

This study investigated the behaviour of geopolymer concrete columns reinforced longitudinally and transversely with GFRP bars. From the experimental results, the following conclusions were made:

- The average bond stress developed in GFRP-geopolymer concrete bond-slip specimens was comparable to that of steel-geopolymer concrete specimens, suggesting that the mechanical interlock and friction forces provided by the sand-coating are enough to properly anchor the GFRP bars in geopolymer concrete or to secure a composite action between the GFRP bars and the geopolymer concrete;
- As the bar diameter and embedment length increases, the average bond stress decreases, owing to several factors such as nonlinear stress distribution along the bonded length and Poisson's ratio effect;
- The bending-moment capacities at crushing failure of the GFRP-reinforced geopolymer concrete beams bars were 20% to 50% higher than the capacity of steel-reinforced geopolymer concrete beam at steel yielding
- The serviceability performance of the GFRP-reinforced geopolymer concrete beams was enhanced by doubling the amount of longitudinal reinforcement; however, strength improvement was not realised.
- The bending-moment capacity of the tested beams were higher than that of the GFRP-reinforced ordinary concrete beams mainly

because of the enhanced mechanical properties of the geopolymer concrete.

- The average compression-strength contribution of GFRP bars was approximately 7.6% of the gross strength of the column.
- The GFRP-reinforced geopolymer concrete columns yielded higher strength compared to GFRP-reinforced ordinary concrete, owing to the higher elastic modulus of geopolymer concrete compared to ordinary concrete, which subsequently result in better compatibility between the GFRP bars and geopolymer concrete.

It can be inferred, therefore, that GFRP-reinforced geopolymer concrete system could be adopted in the construction industry, especially when corrosion resistance, electromagnetic transparency, material greenness, durability, and sustainability are sought.

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Recent developments in tall wood buildings

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Abstract:

Wood has been gaining popularity as a building material over the last few decades. There has been significant progress in technology during this period to push the limits of wood construction. At the same time, it has become more economically competitive to build with wood beyond low-rises. As a result, there has been a noteworthy shift in public perception in terms of acceptance of wood as a material for high-rise buildings. There is a growing list of tall wood buildings that have been constructed in different continents over the last decade. With worldwide population growth and increased urbanization, the trend is expected to continue. This paper summarizes the significant technical advances that have contributed in those achievements and expected to facilitate further developments. Advanced processing and manufacturing techniques as well as mechanized mass production and fabrication facilities are offering improved quality materials, known as engineered wood products, at competitive prices and large quantities. The construction practice is progressing fast implementing efficient designs developed through better understanding of material behavior, utilization of sophisticated modelling tools and new approaches in analysis. Structural systems previously considered impractical with wood are now feasible with members made of wood-based materials that have improved engineering properties. New structural concepts and construction techniques have also been proposed that can enable applications to meet demands from new level of heights and additional challenges such as significant wind and seismic loading. The idea of Hybrid structures involving more than one material such as wood in combination with steel and/or concrete is gaining more and more acceptance within the general engineering community. Publications of design guidelines and code updates complemented by adjustments in policies and regulations have been facilitating widespread adoption of the latest technology.

Keywords:

Wood Construction, Tall Wood Buildings, Structural Systems, Hybrid Structures.

1. Introduction

With increasing number of stories and height, the lateral loads such as wind and seismic become more and more significant. Design of tall structures requires additional attention and special connection detailing to resist lateral load, especially for high seismic demand. For multi-storey buildings lateral deflection and acceleration criteria have to be met while maintaining global stability demands, and this is even more importantly for tall wood buildings. The Murray Groove Building in London (Figure 1) is a prime example of modern tall wood building.



Fig 1: Murray Groove

Along with Europe North America, particularly Canada is forging ahead with research and implementations of tall wood buildings. Over two decades of experience have given the designers confidence to push for greater heights. Unlike most of Europe, the entire Pacific coast of North America is a high seismic area and significant resources have been invested to find solutions for timber structures in the region.

2. Challenges and Initiatives

Traditional light-frame wood building in the United States and Canada was restricted until recently to four or five stories in height in most jurisdictions due to fire safety concerns. In Canada, for example, there are nearly 200 buildings made of industrial old brick and timber up to 8 storeys, about 30m in height, built before 1940 [1]. Construction of such buildings has been prohibited in later decades mainly due to the introduction of combustible vs. non-combustible construction concepts and limits on wooden building height introduced in the building code (NBCC) in 1941.

Recent trends of urbanization are creating the need for design and construction of modern buildings for high density living across the continent. There is also increasing interest in building with locally available sustainable material such as wood. Engineered wood

products have been successfully used in other countries for such construction over the last two decades and it has been also attracting considerable attention in urban regions of North America. Strong governmental support to utilize timber has helped to put Canada in a leading position in North America for tall wood building construction. Manufacturing and utilization of engineered wood products have been gaining momentum in Canada over the past few years, with some of the design approaches imported from Western Europe.

Over the last 10 years, Natural Resources Canada (NRCan) and National Research Council Canada (NRC) has made significant investments through supporting research activities addressing those issues to expand the use of wood in mid-to-high rise construction and facilitate code changes in Canada [1]. Examples of the initiatives are the Network on Engineered Wood-based Building Systems (NEWBuildS) and Mid-rise Wood Building project.

NEWBuildS was a multi-disciplinary Canadian National Science and Engineering Research Council (NSERC) project. The goal of NEWBuildS was to advance scientific knowledge and construction technologies that enabled wood-based products to be used in mid-rise and non-residential construction, or integrated into hybridized construction. The research program of NEWBuildS was established in collaboration with FPInnovations, the wood industry and design community, and was organized into four linked research themes.

A key technical outcome of the Network research was the development of new, and improvement of existing, technical tools for use by design engineers, researchers and product manufacturers to predict product and building system performances. These technical tools included sophisticated mathematical models based on first principles, applied engineering models, process models and experimental techniques.

3. Tall Buildings with CLT

Cross-laminated timber (CLT) is a type of engineered wood product developed in central Europe in the early 1990s and has been used in building applications around the world but predominantly in Europe over the past two decades. It uses dimensioned timber glue laminated, with lamination layers oriented orthogonally. CLT panels can be manufactured into long panels with the width limited only by that of the press. The panels can be pre-cut and pre-grooved into desirable shapes, shipped to the construction site and erected quickly. CLT behaves almost like solid wood in load bearing and thus CLT walls are very efficient in resisting gravity loads. In recent years CLT has become an emerging product for multi-storied timber buildings.

CLT systems are considered well suited for timber buildings more than five stories tall due to their strength and the potential to achieve the required fire rating [2]. Not surprisingly, there has been a worldwide growing trend of constructing tall CLT buildings, as confirmed by the recent Forestry Innovation Investment and Binational Softwood Lumber Council survey of international tall wood buildings [3]. Eight out of the ten buildings surveyed, from five to ten stories in height, utilized CLT as either the main lateral system or as floor panels.

Based on a preliminary study [4] the cost of including CLT in the design can be comparable to reinforced concrete for buildings with eight to fourteen stories in the Pacific Northwest of USA. In a recent survey [5], the lack of adequate knowledge has been identified as the primary barrier for use of CLT in high-rises. To assist with that effort, the Technical Guide for the Design & Construction of Tall Wood Buildings in Canada was published by FPInnovations in 2014 with financial support from NRCan [6]. It has been prepared by a group of more than 85 experts from Canada, United States and other countries. The guide is designed to assist designers, code consultants, developers, building owners, and authorities in understanding the key technical issues and challenges associated with the design and construction of tall wood buildings. It has been prepared to be consistent with the design objectives in 2010 NBCC, the latest published edition at that time.

The guide invokes the conceptual design process and how it is applied to tall wood buildings to instigate thoughts on the building systems through principles and potential solutions. The issues with code compliance following the "alternative solutions" path are discussed. It also includes information to assist the consenting authorities in establishing a process to evaluate a scheme designed following that approach.

Different wood-based structural systems such as platform type, post-and-beam with wood-frame infill, mass timber and associated wall assemblies are presented in the guide. Recommendations are provided for analysis and testing of structural systems for wind and seismic loading to meet the structural design requirements and additional serviceability criteria such as sound insulation and floor vibration control. Details such as design considerations and input parameters for connections and assemblies are also covered. Best practices and standards for prefabrication and inspection of the building assemblies are included. It also covers quality assurance issues associated with personnel, execution and record keeping.

Detailing and Serviceability

Proper connection between panels is an essential element for achieving desired performance of CLT structures. Since the inception of the material,

significant efforts have been devoted to developing different connections types. Most of the connection details suggested for North America have been adopted from the research performed in Europe during the last two decades [7]. However, some innovative connection types have been investigated to allow quick assembly and replacement taking advantage of the prefabrication facility.

Other aspects of structural design e.g. deflection due to short-term loading, creep and long-term performance have been outlined in the CLT Handbooks. They also suggest requirements for satisfactory vibration and acoustic performance and the means to achieve them. Building enclosure design for necessary hygrothermal standards and construction procedure are also covered.

Design considerations for the building enclosure to achieve durability of wooded buildings are mentioned. Information is provided on heat transfer and movement of air and moisture through the building enclosure and within a building. Guidance is also provided on building performance testing by short and long term measurements, monitoring of parameters such as airtightness, vibration, sound insulation, floor and building vibrations, energy efficiency, etc. and necessary building maintenance.

One of the biggest challenges for multi-story wood buildings is the negative perception regarding fire safety. To overcome this, necessary technical information is provided as to how these buildings achieve the fire performance required by the current NBCC's acceptable solutions for non-combustible construction. The guide even addresses issues of safety of firefighters and other emergency personnel responding to a building fire.

Seismic Research

Some regions in North America likely to have tall CLT buildings (e.g., the West Coast of the United States and Canada) have significant seismic risk. Developing solutions for designing tall CLT buildings in seismic regions, therefore, has become a priority for researchers and engineers.

In addition to the development of the physical building system, a shift towards performance-based seismic design philosophy must also be made for the new tall CLT buildings in order to address the evolving needs of the future urban communities. Like existing concrete and steel structures, tall CLT buildings will be expected to perform at current code level or better. It is also desirable for the proposed tall CLT buildings to achieve resilience against major earthquake events with minor and easily repairable damage.

Extensive research on CLT for application in multi-storied construction started in Europe after the early 2000s with a significant increase in construction,

including buildings above five stories. However, the understanding of panelised CLT in lateral force resisting systems was still limited, particularly for western United States and Canada which are high seismic regions. In order to address moderate seismicity in the British Columbia Province of Canada, FPInnovations (FPI) initiated a series of research projects on seismic design of CLT systems. Popovski et al. [8] conducted CLT wall tests on 32 shear walls with different aspect ratio, opening, and panel combinations which identified the inter-panel joints and metal brackets as the main source of ductility in CLT walls for building in seismic regions. Following these tests, Popovski et al. also made the first attempt to estimate the seismic modification factors (R-factors) for a CLT system in the National Building Code of Canada (NBCC) [8]. A summary on the seismic performance and seismic design of CLT structures is part of the FPInnovations' CLT Design Handbook [7].

With knowledge gathered from within North America and Europe, FPInnovations published the CLT Handbook Canadian edition [7] which was instrumental in the design and construction of the first CLT projects in North America. The U.S. edition of the CLT handbook was published through a collaborative effort of FPInnovations Canada, American Wood Council, United States Forest Products Laboratory, Engineered Wood Association (APA), and Woodworks U.S., with funding from Binational Softwood Council, Forest Product Laboratory, British Columbia Forestry Innovation Investment (BCFII), and three CLT manufacturers. The handbook covers a wide range of subjects such as CLT manufacturing, construction, fire and acoustic performance in addition to structural design approaches and lateral load systems design.

Extensive studies to determine seismic design factors for a particular CLT building configuration for both the United States and Canada in accordance with the two codes (ASCE-7 and NBCC respectively) was undertaken by Pei et al. [8,9]. Another robust approach for a range of building configurations has been undertaken at Colorado State University [10], with support from the U.S. Department of Agriculture, to identify seismic performance factors for CLT shear walls for the Federal Emergency Management Agency P-695 methodology in ASCE-7 [10].

United States National Science Foundation is recently funded the NEES-CLT [11] research project that is focused on developing seismically resilient solutions for CLT systems, for tall buildings in the United States with the intention to propose a road map for developing CLT tall buildings in the United States with the first targeted construction in 2020. It was noticed that the societal needs and expectations for tall CLT buildings in seismic regions are not yet well defined and this was also investigated as part of the NEES-CLT project.

The potential market was identified as eight to twenty storey buildings in urban environments. The study found that savings in repetitive architectural patterns, fast modular construction and the potential to save on lifecycle operational costs and resiliency during earthquakes are taken into consideration for cost effectiveness of design options. However, the direct cost of the CLT option was still the main factor influencing the decision on material in most projects and the CLT option had to be of comparable cost while sustaining or exceeding the functionality of its competitors to capture significant market share. Fire-related code provisions, lack of experience, innovation and research funding were identified as additional challenges for introducing CLT construction in the United States.

The recommendations of the project suggested that the parties interested in tall CLT buildings work on manufacturing, code compliance for fire safety, education, and outreach. The CLT industry was also encouraged to work with the steel and concrete industries to develop hybrid structures that include CLT components.

Similar to building systems with other materials, a series of tiered objectives was proposed as performance expectations for tall CLT buildings [9]. Complying with current code requirements was the basic performance objective for the new tall CLT systems. Better-than-code performance was the next level to be offered to the stakeholders. Structural systems providing seismic resilience were expected to perform at the highest performance level achievable. Performances during an earthquake and advantages such as reduced damage and down time afterwards demonstrate the relative efficiency of such systems and can also improve public perception and willingness to implement. The engineering parameters were dictated by application of performance-based seismic design philosophy.

Construction of a 12 storied CLT building in the Pacific Northwest by 2020 (termed "Vision CLT2020") has been set as the goal for the project [12]. That is expected to be a milestone in building tall CLT structures in the United States paving the way for many others of the type all over the country.

4. Tall Wood Building Design Initiatives

To promote the cause further through design and construction of the first examples, the Canadian authorities launched the tall wood building design competition. In 2013, Canadian Wood Council issued a request for Expressions of Interest for design teams to use innovative design and build high-rise wood demonstration projects. Under funding from Natural Resources Canada (NRCan), this initiative links scientific advances with technical expertise to showcase the benefits of innovative wood-based

structural solutions. To support the initiative, a Technical Guide for the Design and Construction of Tall Buildings in Canada was developed by FPInnovations.



Fig 2: UBC Brock Commons

Submissions were reviewed by an Evaluation Team and the three selected projects were: Cathedral Hill2, a Condominium plus Office building in Ottawa which comprises housing with 12 stories and floor area of 11,750 sq. m., Origine, an 11-storied Condominium (Apartments) in Quebec City with floor area of 11,120 sq. m. and a 18 storied Student Residence within University of British Columbia campus in Vancouver with 15,400 sq. m. floor area (Figure 2). Different systems being considered include the post-tensioning system from New Zealand, CLT/Glulam wood systems and Hybrid wood systems. The UBC building is a Hybrid structure with a concrete core. Each project was divided into six key elements/phases: schematic design, design development and construction documents; Research, testing and additional support; building system code acceptance; cost analysis and approvals; construction; post-construction; communications and training. Incremental funds will be allocated to each step at appropriate times. There were challenges involved in mitigating/sharing risks, additional issues/considerations needed on managing intellectual properties and code acceptance. Engagement and education of stakeholders was found to be a key to broader future commercialization. It was also suggested that a common "R&D" plan/matrix applicable to each project is to be developed with design development milestones established and monitored for each proponent group [1].

In 2014, United States Department of Agriculture, in partnership with the Softwood Lumber Board and the Binational Softwood Lumber Council, announced the U.S. Tall Wood Building Prize Competition (USDA, 2014). This competitive prize, open to teams of architects, engineers, and developers, is expected to showcase the architectural and commercial viability of advanced wood products like Cross Laminated Timber (CLT) in tall buildings. The United States

Federal Register announced [10] that “the selected proponent(s) will be the team demonstrating the best ability to utilize new scientific data, to develop technical expertise, and to use incremental funding to safely design, specify, and construct a building of a minimum of eighty feet (80') in height (not including a reinforced concrete podium) in the United States of America that can showcase the application, practicality, and sustainability of innovative wood based structural building solutions in tall building construction”.

Results of the competition were announced in 2015. The two winners were 12-storied mixed-use Framework building in Portland, Oregon (Figure 3) and 10-storied condominium at 475 West 18th in New York City. The winners received support for incremental costs of pioneering wood construction techniques to address the engineering design and code variances needed to incorporate wood technologies into new building sites. The competition required that the winning project team source a share of materials from rural, domestic manufacturers and domestic, sustainably managed forests in order to jumpstart new production and economic opportunities in rural America. The Framework project is going ahead into implementation. Additional research and testing are currently underway; construction is set to start shortly afterwards [13,14].



Fig 3: Framework Portland

In parallel with the demonstration design/ prize competitions, some consultants have already designed tall buildings (Figure 4). Michael Green Architects (MGA) in association with Equilibrium Consultants, both from Vancouver, has designed buildings up to 30-stories tall following the “Finding Forest Through Trees (FFTT)” concept. There has been additional research on the structural system [15]. Chicago-based consulting company Skidmore Owings and Merrill (SOM) has prepared a virtual timber design of a 42-story concrete building built in the 1960s. The design includes CLT floors and framing in combination with concrete.



Fig 4: FFTT Structure

5. Conclusions and outlook

Sufficient understanding has been gained through collective research and development globally to use wood in lateral force-resisting systems of mid-to-high-rise buildings. Among ongoing research in Europe and elsewhere, particular focus has been placed in North America on CLT building design for seismic loading. Current initiatives are looking into ways to apply performance-based seismic design to achieve resilient tall wood buildings in high seismic regions. Past and present initiatives from academia, research organisations, professional organisations and industry groups as well as regulatory bodies and government policies are driving the movement forward.

Significant challenges, however, remain ahead particularly with commercial competitiveness and fire safety. Public perception of wood as a suitable material for this type of construction will be improved with each new application. Direct incentives such as demonstration projects and competitions should go a long way in removing barriers. With continuation of the ongoing activities and favourable conditions, it can be expected that in the near future wood will be established as one of the common materials to be considered for tall building construction in North America.

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Experimental research on the size effect on the compressive strength of recycled aggregate concrete

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Abstract:

An experimental research explored the size effects on the compressive strengths of cubic specimens with natural aggregate concrete and recycled aggregate concrete. 45 sets of cubic specimens with three different cube lengths of 100mm, 150mm and 200mm were under axial loading. Based on the results obtained, a size effects formula to calculate the size conversion factor was suggested and relative parameters were discussed.

Keywords:

Recycled aggregate concrete; cubic compressive strength; size effect.

1. Introduction

Concrete is by far the most widely used construction material in the world. Fine and coarse aggregates constitute about 70% of the total volume in concrete. In recent years, recycled aggregate concrete, obtained from demolished concrete structures, have been considered as an alternative material in the structure engineering to conserve natural resource and reuse the construction waste. The aggregate-mortar interface in the recycled aggregate concrete is much more complex than the natural aggregate concrete, which may lead to the difference in the size effect on the mechanical properties of concretes. Many researchers have investigated the mechanical and durability properties of the recycled aggregate concrete [1-7]. However, our knowledge about the size effect on the mechanical properties of recycled aggregate concrete is rather deficient.

Therefore, this paper studied the size effect of the cubic compressive strength of natural and recycled aggregate concrete with various replacement ratios, analyzed the impact of the replacement ratio on the size effect of the compressive strengths and established a series of formulas that can be extensively applicable for calculating the size effect of the compressive strengths of the recycled aggregate concrete.

2. Experimental Details

Cement

ASTM Type I Portland cement (CEM I 52.5) was used in all concrete mixtures. On Day(D)7 and D28, the compressive strengths were 38.5MPa and 58.1MPa respectively. The chemical properties of the cement are given in Table 1.

Table 1 Chemical composition of cement

composition	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	SO ₃	Loss
(%)	22.64	5.76	4.51	61.98	1.10	2.89	0.51

Aggregates

The coarse nature aggregate (NA) was crushed dolomite. And the river sand was used as fine aggregate. The recycled aggregate (RA) was sourced from precast concrete waste with characteristic compressive strength of 40MPa. The compositions of the NA and RA are given in Table 2.

Table 2 Properties of natural and recycled aggregates

	Particle size (mm)	Water absorption (%)	Crushing value (%)
River sand	0-5	1.23	--
NA	5-20	1.72	9.8
RA	5-20	4.01	14.1

Concrete Mixture

The concrete mixture was prepared and produced in the laboratory. The coarse recycled aggregate were used as 50 and 100% substitutions for coarse natural aggregate. The mix proportion of natural aggregate concrete (NAC) and recycled aggregate concrete (RAC) are listed in Table 3.

Table 3 Mix proportion of concretes

Mix notation	NAC		RAC
Replacement ratio (%)	0	50	100
River sand (kg)	525	525	525
NA (kg)	1120	560	0
RA (kg)	0	560	1120
Water (kg)	182	182	182
Cement (kg)	480	480	480
W/C ratio	0.38	0.38	0.38

Specimens casting and curing

Cubic specimens were prepared in three different sizes respectively, with the side lengths ranged from 100mm to 200mm. For each type of concretes and specimen sizes, five groups of cubic specimens were produced, which means there were 45 groups in total (135 specimens).

Steel molds were used to create all the specimens so that the impact of surface unevenness and dimensional errors would be kept to a minimum and not affect the compressive strength. The evenness tolerance of the steel mold was less than 0.02mm, the dimensional tolerance of the various side lengths was less than 0.1mm and the tolerance of the included angle between two adjacent surfaces was less than 0.3°.

The cubic specimens were demolded 24h after molding, and then moved to a standard curing room for curing, where the temperature was maintained at 20±1°C, relative humidity was maintained at 95% and the curing period of the specimens was set at 28 days.

Test equipment and method

The compression tests were conducted on a YA-2000 electro-hydraulic servo compression-testing machine. Due to the bearing plate of the compression-testing machine being made of steel, its Poisson's ratio was greater than that of the concrete material. Under the action of the vertical load, the lateral deformations of the bearing plate and the concrete specimen were inconsistent, which produces a relatively large frictional resistance at the ends of the specimen and causes the "hoop" effect. The ends of the specimens had oil applied to reduce the impact of the "hoop" effect on their compressive strength. Considering that the compressive strength relates to the loading rate, all specimens were loaded at a rate of 0.3MPa/s to eliminate the impact of the loading rate on the cubic compressive strength of the specimens.

3. Results and discussion

Compressive strength

The cubic compressive strengths of the natural aggregate concrete and recycled aggregate concrete with two kinds of replacement ratios on D28 were measured and are presented in Table 4. The specimens are notated in the form of RAC x-y and NAC -y in the table, where x represents the replacement ratio and y represents the side length of the cubic specimen. The compressive strength presented in the table is the average of fifteen measurement.

For the natural aggregate concretes and recycled aggregate concretes with the two replacement ratios, the coefficients of variation of the cubic compressive strengths were all less than 5%, indicating that the discreteness of the test results were relatively limited. As indicated in Table 4, the cubic compressive strength of the natural aggregate concrete and recycled aggregate concrete shows an obvious size

effect phenomenon, which is manifested as the gradual decrease of the cubic compressive strength as the specimen's geometric dimensions increase.

Table 4 The cubic compressive strength of the concretes.

Mix notation	Compressive strength /MPa	Std. Dev. /MPa	C. v. /%
NAC-100	47.21	1.16	2.5
NAC-150	45.16	1.62	3.6
NAC-200	42.89	1.85	4.3
RAC50-100	45.79	1.36	3.0
RAC-50-150	42.45	1.99	4.7
RAC-50-200	39.46	1.52	3.9
RAC100-100	44.38	1.09	2.5
RAC-100-150	40.11	1.74	4.3
RAC-100-200	36.95	1.57	4.2

Size effect on cubic compressive strength

The concept of the size effect rate of the cubic compressive strength is introduced to quantitatively describe the size effect on the cubic compressive strength of each specimen. The cubic specimens with the side length of 100mm were used as the benchmark against which the cubic compressive strengths of the other specimens (150mm and 200mm side lengths) were contrasted, and the percentage ratio of the difference to the cubic compressive strength of the benchmark specimen was defined as the size effect rate. For each kind of specimen, the size effect rate of the cubic compressive strength, represented by γ , is as follows:

$$\gamma_{150} = \frac{f_{cu,100} - f_{cu,150}}{f_{cu,100}} \times 100\% \quad (1)$$

$$\gamma_{200} = \frac{f_{cu,100} - f_{cu,200}}{f_{cu,100}} \times 100\% \quad (2)$$

where $f_{cu,100}$, $f_{cu,150}$ and $f_{cu,200}$ are the compressive strengths of the cubic specimens with side lengths of 100mm, 150mm and 200mm respectively.

According to the definition of the size effect rate, a higher size effect rate value, γ , reflects a greater compressive strength difference between the specimens of different sizes, and suggests that the size effect on the cubic compressive strength of the concretes is more significant. Fig. 1 shows the size effect rate value of the cubic compressive strength of the concretes changes with changes in the replacement ratio.

The size effect on the cubic compressive strength of the concretes was closely related to the replacement

ratio; with an increase in the replacement ratio, the size effect rate γ was significantly enhanced. The size effect rate γ of the cubic compressive strength of the natural aggregate concrete with a replacement ratio of 0 was about 62% and 50% of those with replacement ratios of 50 percent and 100 percent, respectively. This due to there being a greater amount of defects in the interface between the mortar matrix and the coarse aggregates in the specimen with a higher replacement ratio. Therefore, if the specimen has a greater replacement ratio, greater amounts of energy will be required to destroy it; thus, there will be a stronger size effect of compressive strength in a specimen with a greater replacement ratio.

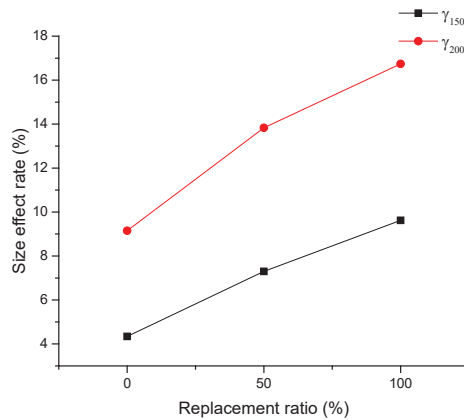


Fig 1: Size effect rate γ of specimens.

Size effect law

On the basis of the test results, we proposed the following equation for calculating the size effect rate with various replacement ratio:

$$f_{cu,x} / f_{cu,100} = a_1(x/100) + a_2 \quad (3)$$

$$a_1 = -0.075 * RR - 0.095 \quad (4)$$

$$a_2 = 0.071 * RR + 1.096 \quad (5)$$

where x is the side length of cubic specimen (in mm), RR is the replacement ratio of concrete.

4. Conclusion

By means of testing and studying the size effect on the cubic compressive strength of the natural aggregate concrete and recycled aggregate concrete with two kinds of replacement ratios and three kinds of geometric dimensions, the paper reached the following conclusions:

(1) There was a size effect phenomenon in the cubic compressive strength in the natural aggregate concrete and recycled aggregate concrete that manifested as the compressive strength gradually decreasing as the geometric dimensions of the specimen increase.

(2) The size effect on the cubic compressive strength of the concretes was significantly enhanced by a increase in the replacement ratio. The size effect rate of the cubic compressive strength of the natural aggregate concrete was 62% and 50% of the recycled aggregate concrete with the replacement ratio of 50% and 100%, respectively.

(3) Based on the test data, a series of formulas were proposed to calculate the size effect on the cubic compressive strength of the concrete.

Acknowledgements

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STRENGTH RECOVERY AND CRACK HEALING OF SELF HEALING CEMENT MORTAR CONTAINING CELLULOSE FIBERS AND BACTERIA

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Abstract:

Concrete is a strong and relatively cheap construction material and is therefore presently the most used construction material worldwide. Formation and progression of cracks under tensile stresses is a major weakness of concrete. Repairing of cracks developed in the concrete requires regular maintenance and special type of treatment which is very expensive. To overcome this problem a self-healing concrete/cement is produced based on the application of mineral producing alkaliphilic bacteria. Metabolic activities of these bacteria on calcium based nutrients results in precipitation of calcium carbonate, which helps to heal concrete cracks and strength recovery. But a continuous decrease in pore size diameter during hydration of cement in concrete probably limited life span of bacterial spores as pore widths decreased below 1 μm , the typical size of bacterial spores. Therefore, a carrier is required which can protect the bacteria spores from mechanical forces during mixing process and in dense cement matrix to increase the viability of bacteria spores in cement mortar. Addition of cellulose fibers to cement concrete helps to reduce cracking and plastic shrinkage of concrete and can be used as carrier for bacteria in cement mortar. In this study, cellulose fibers as a carrier and calcium lactate as a nutrient for *B. Subtilis* 168 bacteria strains are used. This study investigates the encapsulation of bacteria in cellulose fiber and the impact of both additions on tensile strength, crack healing efficiency and compression strength recovery of pre-cracked mortar samples after self-healing. The addition of bacteria with cellulose fiber results in nominal increase in strength recovery as compared to control mortar samples. However, there was no notable change in tensile strength and no healing of cracks was observed in any mortar samples for the dosage of bacteria and nutrients used in this study.

Keywords:

Self-Healing, *Bacillus Subtilis*, Cellulose Fiber, Encapsulation, Strength Recovery

1. Introduction

Cement/concrete is still one of the main materials used in the construction industry, from the foundation of buildings to the structure of bridges and underground parking lots. One drawback, however, is that its massive production exerts negative effects on the environment. It is estimated that cement (Portland clinker) production alone contributes 7% to global anthropogenic CO₂ emissions [1]. Traditional concrete has one issue which is that, it tends to crack when subjected to tension. Some of the property like durability, permeability and strength of the concrete structure is also decreased due to these cracks. Due to increase in the permeability of the concrete, the water easily passes through concrete and comes in contact with the reinforcement in the concrete structure and after some time corrosion starts. Due to this, strength of the concrete structure decreases, necessitating repairs of cracks [2]. The treatment of these cracks by using conventional methods is very expensive. It is estimated that in the United States alone the annual direct cost for maintenance and repair of concrete highway bridges due to reinforcement corrosion amounts to 4 billion dollars

[1]. The repair of cement/concrete structures is not only costly but also time consuming. Especially, the cracking of the surface layer of cement/concrete causes ingress of water and harmful chemicals enter the concrete matrix resulting in degradation of material as well as corrosion of steel reinforcement. Significant researches have been made to make concrete a sustainable material and to reduce the production cost of the cement concrete. Various industrial by products such as fly ash, blast furnace slag and silica fume are these days commonly used as cement replacements in concrete. Although these researches assisted to produce a sustainable cement/concrete and to reduce the construction cost, the methods of sustainable maintenance and repair for cement concrete structures are still under development. Crack formations are typically tackled by manual inspection and repaired by filling of cracks with cement or other synthetic fillers [1]. A promising sustainable repair technique based on microbiologically induced calcite precipitation is investigated (MICP). A mineral producing alkaliphilic bacteria with calcium based nutrients in cement mortar helps in precipitation of calcium carbonate produced by metabolism activities of microbes. The

precipitation of calcium carbonate helps to heal the cracks in cement mortar, results in to increase the overall durability of the material. The cement matrix's pore size decreases with the hydration of the cement, causes mechanical forces on the bacterial spores and decreases the viability of bacterial existence with age of cement mortar. Hence a carrier is required to protect the bacteria from mechanical forces caused by mixing processes and hydration reaction in cement matrix. In this study, cellulose fiber as a carrier for bacteria is investigated. In addition, cellulose fibers in cement mortar helps to increase the tensile strength and resistance to cracking of concrete. So, the combined use of both fibers and bacteria in cement mortar is assumed to resist the crack formation as well as help to heal the cracks and strength recovery of the cement mortar. The investigation has measured the crack healing and strength recovery efficiency of *bacillus subtilis* bacteria encapsulated in cellulose fiber for different ages of curing of cement mortar specimens.

2. Working of Bacteria Based Self-Healing:

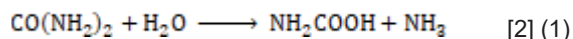
Some types of ureolytic bacteria can be used as an agent for the biological production of calcium carbonate by the hydrolysis of urea or their action on calcium based nutrients. This biological produced limestone helps to heal the cracks in concrete. The pH level of water and cement is up to 13 when mixed together, usually a hostile environment for the bacterial activities. But genus *bacillus* bacteria can lie dormant within concrete for up to 200 years [5] because they have the ability to form spores when subjected to adverse conditions for life (external mechanical and chemical pressure). Bacteria become activated when concrete starts to crack, food is available, and water seeps into the structure. This process lowers the pH of the highly alkaline concrete to values in the range (pH 10 to 11.5) by the dilution of basic concrete environment, where the alkaliphilic bacterial spores becomes activated [4].

The precipitation of calcium carbonate from bacterial action leads to healing of concrete cracks from width ranging from 0.2mm to 0.5mm [4].

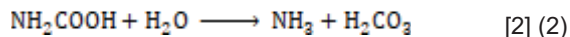
There are two ways to biological production of calcium carbonate by metabolism action of bacteria, which are explained below:

1. Hydrolysis of Urea [2]:

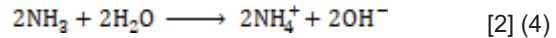
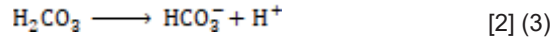
First, 1mol of urea is hydrolyzed to 1mol of ammonia:



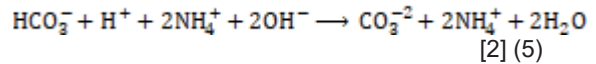
Then carbonate hydrolyses to form additional 1mol of ammonia and carbonic acid:



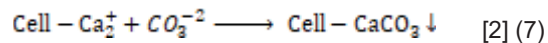
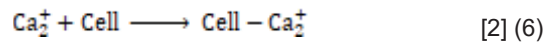
These products subsequently form 1mol of bicarbonate and 2mol of ammonium and hydroxide ions:



The last two reactions shift the bicarbonate equilibrium, resulting in the formation of carbonate ions:



The cell wall of the bacteria is negatively charged and bacteria draw cations from the environment, including Ca^{2+} and results in the precipitation of calcium carbonate:

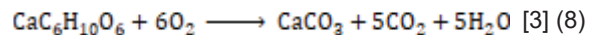


Disadvantages:

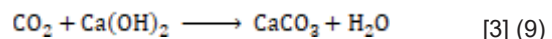
In this process two ammonium ions are simultaneously produced with one carbonate ion. This may result in excessive environmental nitrogen loading [1].

2. The action of bacteria on calcium lactate:

The presence of bacteria with calcium lactate catalysis the production of calcium carbonate. The reaction for the formation of calcium carbonate are explained below:



Formation of calcium carbonate is also evident in concrete without bacteria. This calcium carbonate formation is due to the carbonation of calcium hydroxide, which is one of the major hydration products of cement. However, the production of calcium carbonate in concrete is very slow because less amount of CO_2 is available in concrete for the carbonation process. The CO_2 for this process is available from dissolved CO_2 in the permeated water or from the surrounding atmosphere. In bio concrete the carbon dioxide produced in above reaction accelerate the production of calcium carbonate from carbonation of calcium hydroxide:



Bacteria converts calcium lactate directly into calcium carbonate which is insoluble in water and as result of this metabolic reaction CO_2 is produced which reacts with calcium hydroxide on the spot and does not let it wash away.

The advantage of this process is that the calcium lactate does not have any impact on the settling time of cement when added to concrete. The consumption of oxygen during the bacterial conversion of calcium lactate to limestone has an additional advantage. Oxygen is an essential element in the process of corrosion of steel and when the bacterial activity has consumed it all, it increases the durability of steel reinforced concrete constructions [4].

In this study, we will focus on the process of using calcium lactate as nutrient for bacteria.

3. Right Bacteria for Concrete:

The bacteria from genus *bacillus* can survive in concrete environment as they have the ability to form spores. But there are wide range of bacteria strains from genus *bacillus* which are used by many researchers as a self-healing agent in concrete. All these bacteria found out to be effective in self-healing of concrete. These bacteria have some impacts on the compression strength of the concrete. The impact of different bacteria on concrete strength are tabulated below:

Table 1: Different types of bacteria and their impact on compressive strength of concrete:

Name of Bacteria	Impact on Compressive Strength of Concrete	Remarks
<i>Bacillus Pasteurii</i> ATCC 11859	Increased by 18% [3]	Can be used for self-healing because results in increase in compressive strength
<i>Bacillus Pseudofirmus</i>	Decreased by 10% [3]	Not a good option, results in decrease in compressive strength
<i>Bacillus Sphaericus</i>	Increased by 32.21% [2]	Not a good option causes human diseases [2].
<i>Bacillus Subtilis</i> (JC3)	Increased by 14.92% [2]	Can be used for self-healing as results in increase in compressive strength
<i>Bacillus Subtilis</i> (168)	Increased by 25% [15]	Can be used, as results in increase in strength

For this study, *Bacillus subtilis* 168 bacteria are selected, since it significantly improves compressive strength, produce calcium carbonate and easily available. *B. Subtilis* is rod shaped, found in soil and gastrointestinal tract of human and ruminants, ability to form tough, protective endo-spores, allowing it to bear extreme conditions of cement matrix [15].

4. Nutrients for Bacteria:

A calcium based nutrient is required by alkaliphilic bacteria to produce the calcium carbonate. It has been found that addition of calcium lactate in bacterial concrete is a good approach for precipitation of calcium carbonate to heal cracks because it does not make any impact on the settling time of concrete as does by many sugar based nutrients [4].

For effective working of self-healing concrete the concentration of calcium lactate required has been reported to be between 1% [1] and 4.6% [3] of cement weight.

In this study calcium lactate used equal to 2.5% of cement weight was used.

5. Encapsulation of Bacteria:

The viability of bacterial spores greatly decreases in concrete matrix with time due to decrease in matrix size to 1µm, which is typically the size of the bacterial spores. Therefore, bacteria and nutrients are required to be immobilized in capsules to make sure that the agent should not become active during mixing of concrete and to protect the bacterial spores from the alkaline environment of concrete, mechanical forces in dense concrete matrix and the mixing process. There are many materials available which can be used to encapsulate bacteria in concrete like clay pallets, polyurethane, light weight aggregates (LWA), hydrogel and graphite nano platelets (GNP) etc.

GNP are weak when it comes to multi axial load application due to decrease in pore size of concrete matrix with time and does not provide the best cover to bacteria. However, LWA provides cover during the mixing phase and provides better protection to spores in the concrete as it provides resistance against the pressure developed in matrix due to microstructure development [3].

To increase the viability of bacteria spores in concrete a carrier with micro pores is required which helps to accommodate bacteria spores and protect them from dense concrete matrix over a long time.

In this study, the encapsulation and viability of bacteria spores in cellulose fibers is investigated. This is because the cellulose fiber has high percentage volume of permeable voids [13]. These voids can be helpful for encapsulating bacteria spores.

6. Cellulose Fibers as Reinforcement for Concrete:

Natural fibers have remarkable characteristics of being ecofriendly and recyclable are helpful in reducing greenhouse gas emission associated with concrete. Most of the natural fibers used in concrete are produced from vegetable and wood fibers. Broad availability of these materials in nature made these fibers much cheaper as compared to other types of fibers. Table 2: highlights the cost benefit offered by natural fibers:

Table 2: Price (USD) Comparison for different types of fibers [7]:

Fiber Type		Price (USD/m3)
Steel		7110-11850
Glass		3250-5000
Synthetic	Polypropylene	1620-2700
	Polyethylene	1380-2300
Natural	Sisal	750
	Banana	800
	Coir	600

Cellulose fibers are fibers made with ether or esters of cellulose, which can be obtained from the bark, wood or leaves of plants or from a plant based material [13]. Cellulose is the most plentiful natural polymer on the planet earth, with a global production and decomposition of $\sim 1.5 \times 10^{12}$ tons per year [6]. In recent industrial challenge to successfully meet environment and recycling problems, cellulose is a proposed solution to those challenges as a renewable and biodegradable raw material [6]. Cellulose can be obtained from plants animals, algae, and minerals. However, the plant fiber is the major source of cellulose.

Cellulose fibers have the necessary stiffness and strength because they make hydrogen bonds between the long chains [13]. As well as these fibers are environmentally friendly, skin friendly and bio degradable. Apart from this, high surface area and close spacing of cellulose fibers make them quite effective in the suppression and stabilization of microcracks in the concrete matrix [8]. So, use of cellulose fibres as a reinforcing material in cement concrete can be an environmentally friendly approach.

7. Cellulose Fibers in Bacterial Concrete:

Since, use of cellulose fibres as a reinforcing material in cement concrete is helpful for reducing microcracks in concrete, bacteria as a self-healing agent can be helpful to heal cracks in concrete and combination of both techniques is expected to increase the overall durability of concrete.

In this study, the working of cellulose fiber as a carrier for bacteria in cement mortar is investigated. This is

one of the first studies looking at using cellulose fibers as a carrier for bacteria.

8. Experimental Program:

8.1 Material Properties:

The following sections detail the types and associated properties of different materials used in preparation of cement mortar.

8.1.1 Cement:

General use Ordinary Portland Cement (OPC) of Type 10, as per ASTM C150 [16] specifications, was used in the making of mortar samples.

8.1.2 Fine Aggregates:

Fine aggregates used for the preparation of cement mortar are obtained from the Sechelt pit in B.C. and had a relative dry density and absorption ratio of 2.651 and 0.79% respectively.

8.1.3 Fibers:

Fibers used in this study were obtained from Solomon colors, INC. These fibers are special type of natural cellulose fibers called UltraFiber 500 made from Slash pines and Loblolly in North America. As per manufacturer's declaration, UltraFiber 500 is an alkali resistant cellulose based micro fibers used for secondary reinforcement, provides crack control and have better hydration and bonding properties [19]. A close view of cellulose fibers is shown in Fig 1.



Fig 1: Micro Cellulose Fibers

Use of these fibers in cement mortar also supports the purpose of sustainability as they come from natural renewable resources. General properties of cellulose fibers are represented in table 3:

Table 3: General Properties of UltraFiber 500 [9]

Name of Fiber	Solomon UltraFiber 500
Material Type	High Alkali Resistant, natural cellulose fibers
Average Length	2.1mm (0.083 inch)
Average Diameter	0.00063 inch
Count, fiber/lb	720,000,000

Average Denier	2.5 g/9,000m
Density	1.10 g/cm ³
Surface Area	25,000 cm ² /g
Tensile Strength	750 N/mm ²
Average Elastic Modulus	8,500 N/mm ²
Water Absorption	Up to 80% of fiber weight [10]

8.1.4 Bacteria (*Bacillus Subtilis* 168):

Bacillus subtilis is a gram-positive bacterium, also known as *hay bacillus* or *grass bacillus*, found in the soil and the gastrointestinal tract of human and ruminants [11]. The *Bacillus subtilis* strain 168, cultured and grown at the microbiology laboratory of University of Victoria, are used in this study.



Fig 2: *Bacillus Subtilis* 168 Bacteria Culture

The medium composition used for the growth of bacterial culture is:

Peptone 5 g/ Litre

NaCl 5 g/ Litre

and yeast Extract 3 g/ Litre

0.3 g of Manganous Sulphate (MnSO₄) is also added to the medium to enhance the sporulation of bacteria culture. The medium was first sterilized by autoclaving at 121°C for 20 minutes. Then, the culture was incubated at 35°C with shaking at 200 rpm for 72 hours. The spores were harvested by centrifuging at 5000 rpm for 15 minutes at 4°C. The spore suspension (pellet) was re-suspended in an equal volume of sterile saline and heat shocked at 70°C for

30 minutes and stored at 4°C for several months before use.

The spore concentration was 2.6×10^7 spores per ml of the bacterial suspension.

8.1.5 Calcium Lactate:

Calcium lactate is a white crystalline salt with chemical formula C₆H₁₀CaO₆ [12]. Calcium lactate for this study was purchased from iChemical Technology USA Inc.

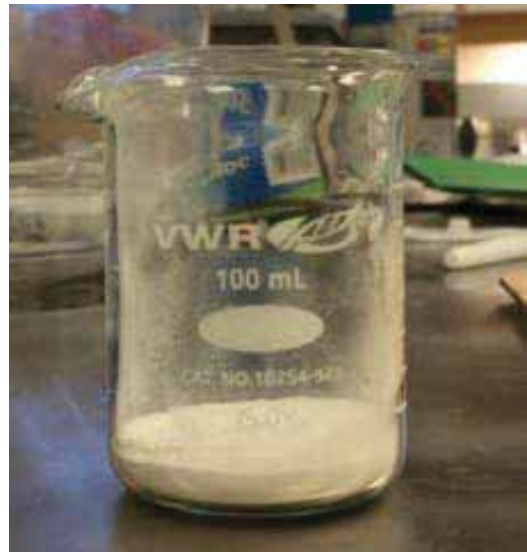


Fig 3: Calcium Lactate (C₆H₁₀CaO₆) Powder

8.2 Mortar Mix Design:

The cement/sand and water/cement ratios for mortar mix design are selected as 0.33 and 0.5 respectively. Four types of mix designs were formulated:

1. CMxx: Control Mortar.
2. CO.25Mxx: Control Mortar with cellulose fibers equal to 0.25% of volume of cement mortar.
3. BMxx: Mortar with *bacillus subtilis* bacteria equal to 1.77×10^7 spores/cm³ of cement mortar and calcium lactate equal to 2.5% of cement weight.
4. B0.25Mxx: Mortar with *bacillus subtilis* equal to 1.77×10^7 spores/cm³ of cement mortar encapsulated in cellulose fibers (0.25% of cement weight) and calcium lactate equal to 2.5% of cement weight.

Where M, B and xx refers to mortar, bacteria and sample number respectively. Decimal fraction indicates the percentage volume of cellulose fibers in cement mortar.

Mix proportion used for mortar is represented in table 4.

Table 4: Mix proportions for cement mortar

Material	Quantities	Units and Remarks
Cement	736	Kg/m ³
Sand	2207	
Water	368	
Cellulose Fibers 0% and 0.25% (by volume)	0 and 2.75	
Bacterial Solution (2.6x10 ⁷ spores/ml)	0.068	ml/cm ³ to achieve 1.77 x 10 ⁶ spores/cm ³ of cement mortar
Calcium Lactate (2.5% of cement weight)	18.4	Kg/m ³

8.3 Test Specimens:

Three mortar cubes of size 50mm and three dog-bone shape briquettes of size 1" (depth) x 3" (length) x 1" (Width at center) were prepared for each mix design (CMxx, C0.25Mxx, BMxx and B0.25Mxx).

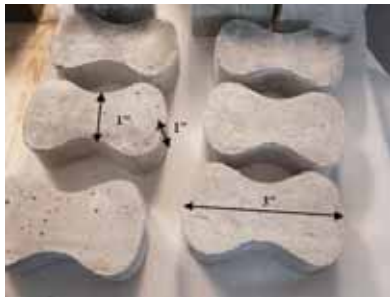


Fig 4: Briquette Samples

8.4 Encapsulation of Bacteria in Cellulose Fiber:

Required quantity of cellulose fibers was kept soaked in required quantity of bacterial solution for B0.25Mxx mix design for 24 hours.

8.5 Mixing, Curing and Setting Procedure:

Ingredients for different mixes were batched out as per final volume of mortar required by using an electronic weighing balance. A homogeneous blend of cellulose fibers was achieved by preparing fiber slurry in water, followed by mixing in sand for a minute by hand mixing in a bowl. Afterward, required cement, and water quantities were added to the paste, calcium lactate was added for BMxx and B0.25Mxx mix designs and mixed for another minute. Bacterial solution was added to the required water quantities for bacterial mix designs so that spores can distribute

throughout the mortar matrix. Figure 5: shows the manual mixing equipment:



Fig 5: Mortar Mixing

Once the uniform mix was achieved, the mortar was poured into cube and briquette molds.



Fig 6: Mortar Mix in Cube and Briquette Molds

To ensure maximum compaction and removal of entrapped air, manual compaction was done using a tapping rod. The mortar was placed in molds in two equal layers and each layer was tapped 25 times. After compaction, molds were covered with a plastic sheet and placed at room temperature for next 24 hours. Demolding was carried out after 24 hours and samples were placed in water tub maintained at 23 ± 2° C after appropriate labeling based on the mix design.

8.6 Testing Procedure:

To investigate the effectiveness of bacterial healing with different ages of curing, cubes were pre-cracked after 7 and 14 days of curing. The cubes were subjected to compressive testing machine under controlled compressive loading till visible cracks appeared on the surface. The cracks were measured and marked for further examination of self-healing. The pre-cracked cubes were continued to cure for next 14 days and crack width was measured after this additional curing. In addition to these tests, the pre-cracked cubes were tested for compressive strength

after 14 days of curing to investigate the strength recovery of bacterial mortar.

One cube from each type of mix design was subjected to above tests.

Apart from this one dog-bone sample of each mix design was tested for tensile strength after 7 and 14 days of curing by using uniaxial testing machine.

8.6.1 Crack Induction:

Cracks were induced in one cube of each type by using uniaxial compression testing machine after 7 days and 14 days of curing. Samples were loaded until a crack was observed on the cube surface. Afterwards, Cracks were labeled with a unique name to record data for future analysis of crack widths.



Fig 7: Induced Crack in a Cube

8.6.2 Measurement of Cracks:

The width of cracks induced in the cubes was measured by using crack measuring microscope. The accuracy of measurement was up to 0.02mm.



Fig 8: Crack Measuring Microscope

8.6.3 Compression Test:

Pre-cracked cubes were tested for compressive strength after 14 days of curing for self-healing, to investigate the strength recovery due to bacterial action.

ASTM C 109 [17] states the method to determine the compressive strength of cement mortars cubes of size 50mm. Cubes were tested under a uniaxial compression testing machine and peak load was recorded at the point of failure. Figure 9 shows the fractured mortar cubes after testing.

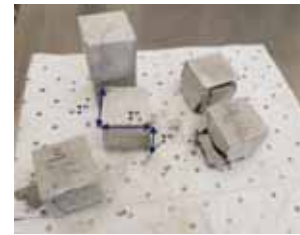


Fig 9: Mortar Cubes after Compression Testing

Loading rate was set within the standard's specified range. Compressive strength of each mortar cube was calculated using a formula:

$$\text{Compressive strength (MPa)} = P/A$$

P = Peak load (N)

A = cross section area (mm²)

8.6.4 Tensile Test:

ASTM C 307 [18] states the procedure to evaluate the tensile strength of a mortar mix under uniaxial tension testing in the form of a dog-bone shape briquette sample.

One sample of each mix design was tested using the test setup shown in Figure 10. Each specimen was clamped in a pair of grips which were attached to a testing frame having a load capacity of 7.1 kN. Data was recorded at 25 hz frequency, and a crosshead displacement rate of 0.48 mm/min was used.



Fig 10: UTM Setup

The following formula was used to compute the uniaxial tensile strength of specimens;

$$\text{Tensile strength (MPa)} = P / (b \times d)$$

Where;

P = applied load (N)

B = Width at the center of briquette specimen (mm)

D = Depth at the center of briquette specimen (mm)

9. Results and Discussion:

Results from different tests are presented and discussed here to determine the efficiency of self-healing using bacteria in different mixes. These results include the measurement of crack width, visual inspection of cracks, compressive strength recovery of pre-cracked samples and tensile strength of mortar samples.

9.1 Crack Width Analysis:

Mortar mix containing, bacteria only (BMxx) and bacteria with cellulose fiber (B0.25%Mxx) were pre-cracked after 7 and 14 days of curing. The cracks were marked, and respective width was measured. The different crack width for different samples is represented in table 5:

Table 5: Crack Widths for Pre-Cracked Cubes

Sample Name	Crack Name	Size of Crack (mm)	Remarks
BM1	C1	0.06	Bacterial mortar 7 days of curing
BM1	C2	0.6	
BM1	C3	0.2	
BM1	C4	0.12	
B0.25M1	C5	0.1	Bacteria + fiber 7 days curing
B0.25M1	C6	0.06	
BM2	C7	0.12	Bacterial mortar 14 days of curing
BM2	C8	0.12	
BM2	C9	0.08	
BM2	C10	0.08	
BM2	C11	0.1	
BM2	C12	0.12	

Sample Name	Crack Name	Size of Crack (mm)	Remarks
B0.25M2	C13	0.06	Bacteria + fiber mortar 14 days of curing
B0.25M2	C14	0.08	
B0.25M2	C15	0.2	
B0.25M2	C16	0.2	
B0.25M2	C17	0.04	
B0.25M2	C18	0.1	

The cracks were observed after 14 days of curing of pre-cracked specimens and there was no observed visible healing of cracks. Figure 11 shows the comparison of 0.1mm size of cracks for both type of mortars after 7 days of cracking.

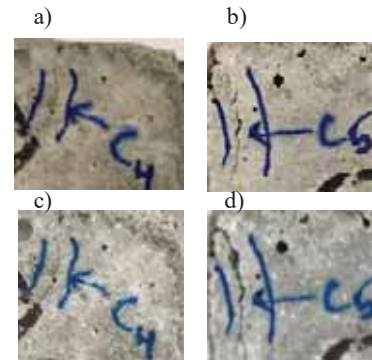


Fig 11: Comparison of 0.1mm Sized Cracks
a) BM1 mortar 7 days crack. b) B0.25M1 mortar 7 days crack. c) BM1 mortar 14 days cured crack. c) B0.25M1 mortar 14 days cured crack.

There are several possible reasons for the ineffective healing of cracks. In this research, calcium lactate equal to 2.5% of cement weight has been used. However, Wasim and Muhammad [3] used 4.86% of cement weight to ensure enough availability of calcium lactate to bacteria. So, more quantity of calcium lactate is required for an effective self-healing of cracks.

Secondly, there are possibilities of loss of healing agent in to water surrounding cured samples, resulting in decreased self-healing efficiency [14]. Chunxiang and Huaicheng noted that transportation of CO₂ to cracks is necessary for effective healing of cracks by bacterial action [14]. Air could be pumped in curing water to keep the adequate amount supply of CO₂. Loss of healing agent could be eliminated by spraying the healing agent only in to cracks instead to adding healing agent in to whole mix.

9.2 Compressive Strength Results:

7 and 14 days cured pre-cracked samples were tested after 14 days of curing to examine the strength recovery of bacterial mortar. One number of sample for each type of mortar was tested. The results for compressive strength are represented in table 6.

Table 6: Recovered Compressive Strength

Sample Name	Post Crack Compressive Strength (Mpa) after 14 days of Healing	Remarks
BM1	37.16	Bacterial mortar, cracked after 7days of curing
B0.25M1	45.56	Bacteria + cellulose fiber mortar, cracked after 7days of curing
CM1	36.84	Control mortar cracked at 7days of curing
C0.25M1	37.36	Mortar + fiber cracked at 7days of curing
BM2	39.92	Bacterial mortar, cracked at 14days of curing
B0.25M2	44.72	Bacteria + cellulose fiber mortar, cracked after 14days of curing
CM2	40.4	Control mortar cracked at 14days of curing
C0.25M2	38	Mortar + fiber cracked at 14days of curing

Above results shows, mortar containing cellulose fiber with bacteria increase strength recovery by 21.9% from mortar containing cellulose fiber only after 7 days of curing. There were not any significant strength recovery differences noticed between the control mortar and mortar with bacteria only. However, more samples are required to be tested to eliminate the standard deviation errors.

9.3 Tensile Strength Results:

Dog-bone briquettes of distinct types of mortar were tested after 7 and 14 days of curing. One number of sample of each type was tested. The results are represented in table 7.

Table 7: Tensile Strength of Mortar Samples

Briquette Name	Tensile Strength (Mpa)	Remarks
BM1	1.97	Bacterial mortar 7days cured
CM1	3.07	Control mortar 7days cured
B0.25M1	2.93	Bacteria + fiber 7days cured
C0.25M1	2.95	Mortar + fiber 7days cured
BM2	3.24	Bacterial mortar 14days cured
CM2	2.53	Control mortar 14days cured
B0.25M2	3.49	Bacteria + fiber 14days cured
C0.25M2	3.36	Mortar + fiber 14days cured

There was no notable change in tensile strength was observed for mortar, containing cellulose fiber only and containing fiber with bacteria. Results for samples without fiber shows contradictory results, BM1 has very low strength as compare to CM1 after 7 days of curing, opposed to that BM2 has higher strength than CM2 after 14 days of curing. These errors are may be due to standard deviation. Hence, more samples need to be tested to minimize the standard deviation in results.

10. Conclusion

Based on the results achieved in this study following conclusion may be drawn:

1. There was no visible crack healing observed in all types of pre-cracked samples. Sufficient calcium based nutrients (more than 2.5% of cement weight) and CO₂ in curing water should be available for effective self-healing of cracks.
2. The addition of bacteria alone did not show any notable strength recovery as compared to control specimen after 7 days of curing. However, Bacteria with cellulose fiber results in increase in strength recovery by 21.9% from control mortar containing fiber only.

3. There was not any change in tensile strength was observed after addition of bacterial in control and cellulose fiber mortar.

Acknowledgements

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Influence of vegetation on pedestrian thermal comfort in a street canyon

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Abstract:

Vegetation in urban environments has a cooling effect on the microclimate and can thereby mitigate the Urban Heat Island (UHI) effect that is increasing due to urbanization. Vegetation can provide natural cooling in the form of transpirative cooling and by providing shading to the nearby surfaces. However, vegetation such as trees also has an impact on the ventilation of cities, which can negatively affect urban convection-driven processes, e.g., heat removal. In the present study, the influence of vegetation (i.e. a row of trees) on the microclimate of a street canyon is investigated. The thermal comfort provided by vegetation is quantified using the Universal Thermal Climate Index (UTCI). The study finds that the natural cooling due to shading is significantly higher than the cooling due to transpiration. Furthermore, the natural cooling effect is also seen to be present during night-time even after the plant stops transpiring. It is caused by reduced building surface temperatures resulted from the shadowing and transpirative cooling.

Keywords:

CFD, thermal comfort, transpiration, UHI, vegetation.

1. Introduction

Vegetation in urban environments has a natural cooling effect on the urban climate and can mitigate Urban Heat Islands (UHI). Vegetation provides natural cooling as the leaves extract heat from the surroundings during evapotranspiration and as the tree foliage intercepts the solar radiation, providing shading to the ground and nearby building surfaces. However, trees can also negatively influence the ventilation characteristics in cities as the foliage obstructs air movement, which affects airflow at pedestrian levels. As a result, the net impact of vegetation in cities is dependent on various parameters, requiring advanced numerical models to predict the impact of vegetation on pedestrian comfort accurately.

The interaction between vegetation and the environment is a multi-physical phenomenon. Vegetation exchanges momentum, heat and mass with the air. A computational fluid dynamics (CFD) approach (Hiraoka, 2005; Liang et al., 2006) is shown to be able to identify the interaction between vegetation and environment, where the vegetation is modeled using a porous medium approach. Such an approach has also been used to study the influence of vegetation in urban areas (Bruse and Fleer, 1998; Gromke et al., 2014; Robitu et al., 2006), which is shown to provide a better estimate of the thermal impact of vegetation. Therefore, an urban microclimate model that can model the airflow and radiation in an integrated approach provides the mean to accurately assess the environmental impact of vegetation for a given complex urban topology.

In this study, we investigate the cooling potential of vegetation, such as a row of trees, on the microclimate

of a street canyon using a CFD model in OpenFOAM. Prior to this study, the cooling effect of vegetation (Manickathan et al., 2018) and the microclimate of a street canyon (Kubilay et al., 2017) were studied separately. The present study is a continuation of these works towards modeling their interactions. A radiation model is developed to model the short-wave and long-wave radiative heat fluxes between the leaf surface and the surroundings. Using the developed model, it is possible to study the influence of transpirative cooling and shading due to vegetation on pedestrian thermal comfort inside a street canyon. The thermal comfort for pedestrians is evaluated using Universal Thermal Climate Index (UTCI).

2. Materials and Methods

2.1 Numerical model

The flow field is numerically modeled by solving the Reynolds-averaged Navier-Stokes equations (RANS) with the realizable $k - \varepsilon$ turbulence closure model (Eq. 1):

$$\frac{\partial \phi}{\partial t} + \nabla \cdot (\bar{\mathbf{u}} \phi) = D_\phi \nabla^2 \phi + S_\phi \quad (\text{Eq. 1})$$

where

ϕ	=	$\{ \bar{\rho}, \bar{\rho} \bar{\mathbf{u}}, \bar{\rho} \bar{E}, \bar{w}, k, \varepsilon \}$
ρ	=	air density [kg m ⁻³]
$\bar{\mathbf{u}}$	=	velocity vector [m s ⁻¹]
$\bar{E}$	=	energy per unit mass [J/kg]

$\bar{w}$	=	humidity ratio [kg kg ⁻¹]
k	=	turbulent kinetic energy TKE [m ² s ⁻²]
ε	=	TKE dissipation rate TDR [m ² s ⁻³]
D_ϕ	=	diffusion coefficient of ϕ [m ² s ⁻¹]
S_ϕ	=	source of ϕ [ϕ s ⁻¹]

The vegetation model is integrated into the CFD solver as a porous medium, by including the necessary source/sink terms, S_ϕ , for heat, mass and momentum fluxes, with additional closure for the turbulence effects due to vegetation. A detailed summary of the numerical model is provided in Manickathan et al. (2018). The heat and mass exchanges between the vegetation and air are determined from the leaf energy balance (Eq. 2) :

$$q_{rad,leaf} - q_{lat,leaf} - q_{sen,leaf} = 0 \quad (\text{Eq. 2})$$

where

$q_{rad,leaf}$	=	radiative heat flux [W m ⁻²]
$q_{lat,leaf}$	=	latent heat flux [W m ⁻²]
$q_{sen,leaf}$	=	sensible heat flux [W m ⁻²]

A similar approach is used by various other authors (Boulard et al. 2008; Bruse and Fleer, 1998; Dauzat et al. 2001; Hiraoka, 2005). The developed radiation model enables to model the impact of the diurnal variation of solar intensity and direction, and the long-wave radiative fluxes between vegetation and nearby urban surfaces.

The diurnal variation of the microclimate is modeled using a pseudo steady-state approach, where the governing equation of the air domain, integrated with vegetation, is solved using a steady-state approach at 10-minute intervals. The heat and mass transport in the building materials is solved using an unsteady approach. A detailed summary of the solution algorithm for coupling the vegetation model with airflow model is presented in Manickathan et al. (2018) and the solution algorithm for coupling the air domain with the solid domain is presented in Kubilay et al. (2017).

2.2 Simulation setup

The simulation is performed for a street canyon composed of two buildings of 10 × 50 × 10 m³ ($x \times y \times z$) surrounding a rectangular vegetation zone of 2 × 10 × 4 m³ in the center as shown in Fig. 1. This vegetation zone represents a row of trees with a foliage height of 4 m (with $z_{min} = 4$ m and $z_{max} = 8$ m), leaf area density $LAD = 10$ m² m⁻³, leaf drag coefficient $c_d = 0.2$ and leaf size $l = 0.1$ m. A detailed description of the initial conditions, boundary conditions and the grid resolution is presented in Kubilay et al. (2017). The meteorological data are based on a typical

meteorological year and total solar radiation intensity for clear sky for 21st of June in the city of Zurich, Switzerland.

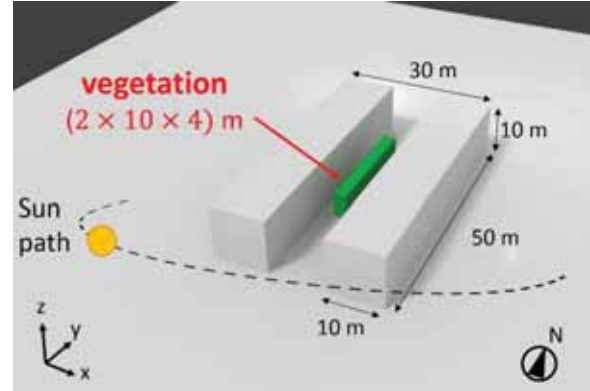


Fig. 1: The simulation setup of a street canyon composed of two buildings measuring 10 × 50 × 10 m³ with vegetation band of size 2 × 10 × 4 m³ in the center. The setup is based on the study of Kubilay et al. (2017) with wind.

3. Results and discussions

The influence of vegetation on the microclimate of the street canyon (depicted in Fig.1) is studied using the developed numerical model. The natural cooling provided by the row of trees is determined by comparing the setup with and without vegetation, “V” and “NV”, respectively. Fig. 2 shows the change in air temperature, $T_v - T_{nv}$ (°C) at noon (12 pm), when the sun is directly above the street canyon. The vegetated region is indicated by the dashed outline. From the figure, two distinct regions of cool zones can be identified. The first region is at the vicinity of the vegetation with a temperature change of around -2 °C. This cool zone results from the transpirative cooling effect of vegetation.

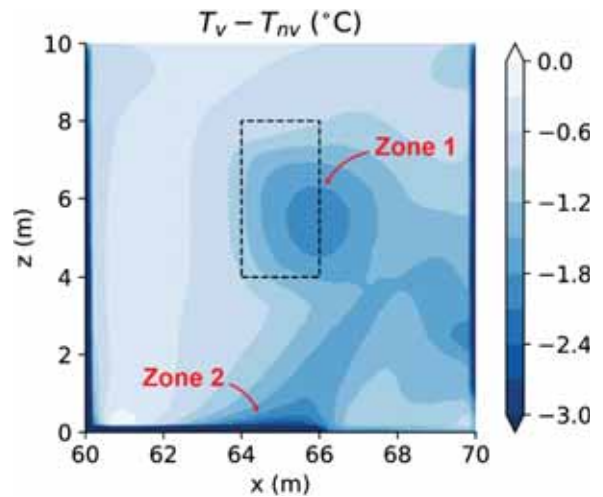


Fig. 2: Temperature drop, $T_v - T_{nv}$ (°C) due to vegetation at noon (12 pm) in the center of the street canyon (at $y = 125$ m). The vegetated zone (i.e., row of trees) is indicated by the black dashed line.

The second zone is the region close to the building wall, where the shadow of the tree was present earlier during the day. This cooling region, resulting from tree shading, is seen to be more effective than the transpirative cooling region, showing a temperature drop of more than -3°C . Furthermore, at the current location of the shadow, the cooling air is seen to be convected away from the wall, and interacts with the cool zone. This indicates that, in addition to transpirative cooling, the tree-shade cooling plays a vital role in improving the microclimate. It is also evident that, as a result of the combined influence of transpirative and tree-shade cooling, the overall surface temperature of the street canyon is lower.

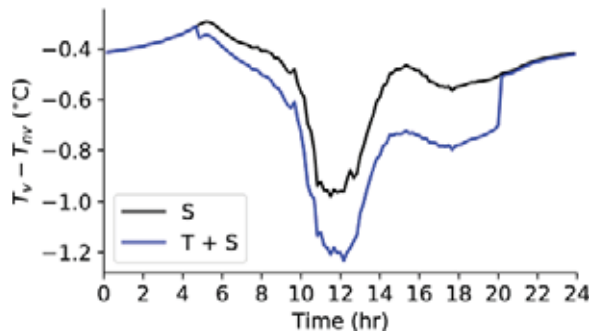


Fig. 3: Diurnal variation of the temperature drop, $T_v - T_{nv}$ ($^{\circ}\text{C}$) for two configurations: with shading (S) and with transpiration and shading (T+S). The temperature drop is probed below the vegetation in the middle of the street canyon at $x = 65\text{ m}$, $y = 125\text{ m}$ and $z = 2\text{ m}$, indicating the influence of a pedestrian.

To quantify and distinguish the natural cooling associated with transpirative cooling and the natural cooling associated with tree-shade cooling, two simulation cases are compared: transpiration and shaded case (T+S) and shade only case (S). Fig. 3 compares the diurnal variation of the temperature drop, $T_v - T_{nv}$, for these two configurations, for a single measurement point below the row of trees at $x = 65\text{ m}$, $y = 125\text{ m}$ and height of $z = 2\text{ m}$. The peak reduction in air temperature below the tree is seen to occur at noon, when the point is under the shadow. The configuration "S", with only shadow, shows a peak air temperature drop of around -1.0°C whereas with transpiration (T+S), an additional temperature drop of -0.2°C is found. Therefore, the tree-shade cooling is dominant here. Furthermore, studying the diurnal variation, it is evident that the cooling effect of vegetation is also present during the night time, even after transpiration and tree shade are no longer present, with a temperature drop of around -0.4°C . This indicates that a reduction in the heat storage inside the buildings has a prolonged benefit to the urban climate.

The influence of vegetation on pedestrian comfort is determined by evaluating the Universal Thermal Climate Index (UTCI) ($^{\circ}\text{C}$) (Fiala et al., 2001; Manickathan et al., 2018). We position a pedestrian

under the tree, Fig. 4 shows the diurnal variation of the UTCI for three different cases: setup without vegetation (no veg), setup with only shading vegetation (S) and setup with transpiring and shading vegetation (T+S). The calculated UTCI (below the trees at $(x, y, z) = (65, 125, 2)\text{ m}$) shows that the comfort perceived by the pedestrian with and without transpiration is identical. The perceived change in comfort is simply due the change in radiative exchanges, influenced by the vegetation. During night time, the UTCI with vegetation is slightly higher which is possibly due to the long-wave radiation emitted from the vegetation. The thermal comfort provided by the vegetation is most significant when the tree intercepts the solar radiation. At noon, when the measured point is in the shadow of the tree, the UTCI is seen to drop by around 7°C , indicating the substantial benefit of the shading on the thermal comfort. In contrast, transpirative cooling is seen to negligibly influence the comfort factor for a pedestrian standing near the tree.

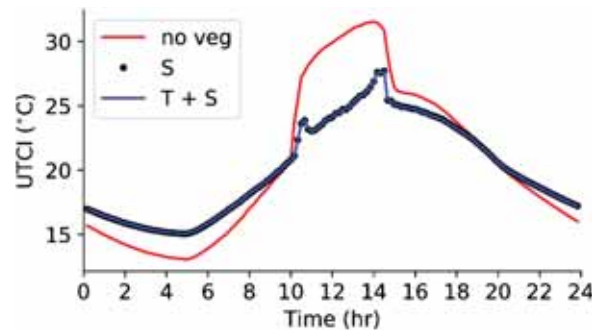


Fig. 4: Diurnal variation of $UTCI$ ($^{\circ}\text{C}$) for a pedestrian standing below the tree at $z = 2\text{ m}$ for various configurations: no vegetation (red), vegetation with no transpiration (black), vegetation with transpiration (blue). Note that the black dots are exactly behind the blue line.

4. Conclusions and outlook

The present study investigates the influence of transpirative and tree-shade cooling on the microclimate of a street canyon. The study shows that both shading and transpiration have a direct influence on the temperatures measured in the street canyon. Furthermore, it is evident that tree-shade cooling is substantially larger than the transpirative cooling and, for the position of a pedestrian under the tree, the thermal comfort, measured through Universal Thermal Climate Index (UTCI), is only affected by the tree-shade cooling. In contrast, the transpirative cooling is seen to have negligible influence on the thermal comfort. Future studies will investigate the influence of environmental and vegetation properties on the impact of transpirative and tree-shade cooling. Additionally, the transpiration rate will be coupled with the soil moisture to determine the influence of root water availability on the impact of transpirative cooling.

Acknowledgements

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A Bottom Up Statistical Building Stock Model for the City of Victoria

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Abstract:

Creating a useful model of any system requires high-quality information about the inputs and outputs of that system. In order to model and optimize energy systems, the demand for energy must be determined alongside possible sources of supply. A model of the building stock of the City of Victoria was created in order to generate a set of spatially accurate and representative energy demand data. This was done by combining existing datasets obtained from the City of Victoria, Statistics Canada (StatsCan), and Natural Resources Canada (NRCan), and mapping variables between these datasets. The City of Victoria provided high spatial resolution building data (building use type, footprint area, height and location). This data was mapped to neighbourhoods consisting of around two hundred buildings using the StatsCan dataset, which allowed us to add the correct age of construction and the number of households and occupants per building type. The resulting representation was then mapped to NRCan energy use data to get an estimate of the energy use of the building stock for the City of Victoria which is highly resolved both spatially and with regards to building characteristics. The final dataset therefore describes the energy use of the city in a way that can easily be disaggregated into different combinations of neighborhood, age and use type. This will form the basis for further studies regarding energy systems changes, building retrofit programmes and city planning decisions

Keywords:

Building stock, energy modeling, bottom up, statistical

1. Introduction

Residential and commercial buildings account for a significant portion of energy use. Therefore, municipalities are considering the building stock in their strategies for reducing emissions. Building stock modeling is a very useful tool for municipalities to get a sense of the kinds of buildings that exist in their area, as well as their energy use. This can then be used in determining where to target policies in order to meet their climate change mitigation goals.

There are two main methods of creating a building stock model: top down and bottom up [1,2]. Top down method involves using aggregated high-level data and statistics to draw conclusions about the building stock. They are beneficial in that they use aggregated data that is more easily available, and avoid detailed technology descriptions. The downside is that it is limited in its ability to assess individual changes to buildings, such as a change of heating system type. It is also not spatially resolved, or at least not at high resolution.

Bottom up models involve using data at an individual building level and compiling these for all the building types in the stock [3]. This has the advantage of being a higher resolution with the ability to look at targeted policy in certain specific areas. This can also be resolved spatially if that data is available. Naturally this requires detailed data for individual buildings to be available which is not always the case.

The method used for this building stock model is to some extents a hybrid of these two methods, referred to as “bottom up statistical” in [1]. It uses a bottom up design for the data that is available, and to get the spatial attributes, but uses high-level aggregated data when building level data is unavailable. Building use type, height, number of storeys, footprint areas, age, and GPS coordinates are all used for the bottom up design, with energy use values obtained using high-level aggregations due to data not being publicly available.

A bottom-up engineering model is another option that analyses energy use down to single building level. The challenge with this method is that detailed building data regarding the building envelope and systems is needed, but often not available. This results in many assumptions that need to be made, which reduces accuracy. In addition, this method does not implicitly include occupants influences on energy use. Statistical models have these factors included implicitly in their aggregated values.

One example of a bottom-up building stock model for Canada is by L. Swan et al. [4], which assembled a building stock representation that is statistically representative of Canada’s residential stock, with nearly 17,000 detailed building entries.

This method has the advantage of being building level and includes spatial elements, but does not require detailed building data, which is not currently available publicly, making it easier to develop and use. As more

data becomes available, it can be integrated to improve the model.

The method used to construct the building stock model is appropriate because it makes use of the existing GIS database with the building use distributed how they appear in reality. This is inherently more accurate than assuming a statistically representative distribution of Canada's building stock, such as [4]. In situations where building use types are not known, then assuming a distribution is acceptable, however, that is not the case here.

2. Data Sources

Figure 1 shows the different databases that were used to make the building stock model and the flow of data from each.

The *City Database* was obtained from the City of Victoria and contains aerial LIDAR data consisting of building footprints, height, GPS coordinates, and elevation, as well as other building information that was available digitally.

The *Survey of Household Energy Use 2011* [5] is a survey performed by NRCan to determine the how much energy is being used in different kinds of residential buildings in Canada and for what purpose. It contains detailed information about energy use based on the building type, age and number of occupants, as well as a breakdown of what kinds of appliances or other plug load items dwellings typically have (computers, video games consoles, etc.). This was the most detailed and relevant residential energy

use data available on which to base the energy portion of the stock model.

The energy per square meter values for each residential building type and age bracket is shown in Fig 2. Fig 3 shows the per square meter energy use for commercial and institutional buildings.

A few of the energy use values in Fig. 2 go up for the more recent age brackets. This is counter intuitive, since usually building performance increases in newer buildings and hence energy use goes down. One potential reason for this increase, especially in the high-rise apartments is likely due to the higher proportion of glass in facades. Glass has a much lower insulating value than a typical wall does, so thermal losses are increased. It could also be due to contiguous balcony designs without thermal breaks. This also increases thermal losses by making the balconies behave like cooling fins on heat sinks

The *Comprehensive Energy Use Database* [6] contains energy use data for residential, commercial, institutional, and industrial building use types at the province level. This data is not as detailed for residential buildings as SHEU2011, however it is a useful source of data on commercial and institutional buildings

Statistics Canada census data is available at the level of Dissemination Area (DA) [7]. A DA is roughly equivalent to a neighbourhood of about 200 to 500 buildings. It contains a large amount of demographic information, but the parts use for this stock model are the land area, the distribution and number of building types, and the number of people living in each DA.

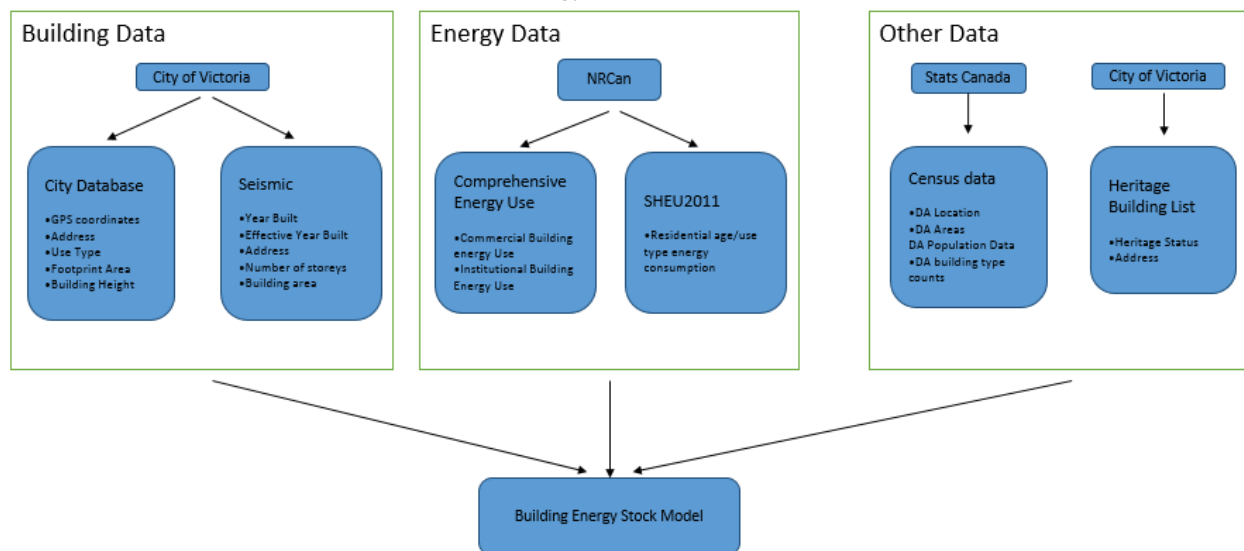


Fig.1: (above) Flow chart of databases used, and which data components came from which source.

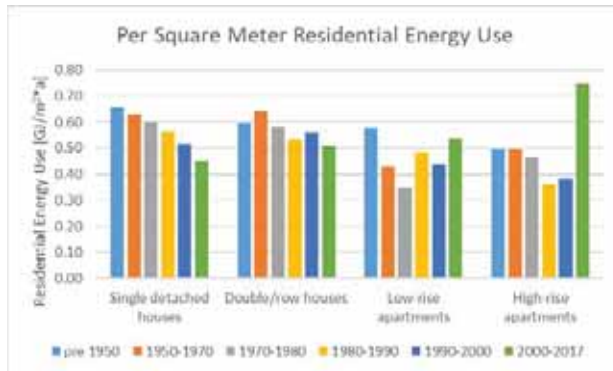


Fig 2: Per square meter residential energy use values from SHEU2011.

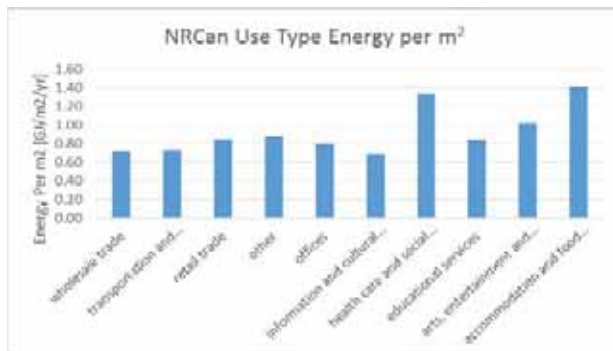


Fig. 3: NRCan use type energy consumption per square meter for commercial and institutional buildings.

The *Heritage Building List* is a list of registered or designated heritage buildings in Victoria. This was used to add a heritage designation to building entries in the model. This is important because heritage buildings are restricted in some respects to the kinds of retrofits that can be performed on them that could affect their heritage attributes. This is mostly added with the expectation that it will be useful in future analysis to do with energy retrofits.

The *Seismic Database* was created as part of the Citywide Seismic Vulnerability Assessment of the City of Victoria produced by VC Structural Dynamics LTD, but was obtained through the City of Victoria.

3. Methodology

There were 72 use types in the City Database, which was reduced to three categories, residential, commercial and institution (C&I), and industrial (I). C&I and industrial buildings were then separated into ten categories each, however some of these were not present in the city.

Residential buildings were sorted into four categories: single detached houses, double/row houses, low-rise apartments, and high-rise apartments. These four

categories were also broken down into 6 age categories that match the SHEU2011 categories: pre 1950, 1950-1969, 1970-1979, 1980-1989, 1990-1999, 2000-2011. The SHEU2011 dates from 2011 and so does not have information about buildings newer than 2011. As a result, buildings newer than 2011 were allocated energy data for the 2000-2011 period. C&I data do not have energy use based on age. Industrial building data on a per floor area basis is not available, only industry totals for the province. As a result, industrial buildings are not included in the stock model energy calculations, however they are still included in the database. The entries for industrial use types will still be present, however the energy use for those use types is not calculated.

In order to determine the number of storeys, sub-grade storeys and building ages, the Seismic Database was used. This database was partially created by VC Structural Dynamics and merged with the database maintained by BC Assessments. The buildings in the stock model were cross referenced to buildings in this database, based on address so that the final stock model would have all the information needed to estimate its energy consumption.

Statistical information for each DA gives the number of buildings, population demographics, land area as well as total numbers of residential housing types. The grouping of buildings in each DA are such that they could be useful in determining the feasibility of district energy systems or other systems where proximity is important. The DA polygons were plotted in GIS software along with the coordinates of all the buildings, which was used to determine which buildings were in which DA.

The heritage building database was also used to determine which buildings were designated as heritage buildings. This is important because it could limit the type and extent of energy retrofits or other development that could be implemented in order to preserve the historical significance of the building or neighbourhood.

The data on energy use comes from two different databases, the Survey of Household Energy Use 2011 (SHEU2011) and the Comprehensive Energy Use (CEU) database, both produced by Natural Resources Canada (NRCan). The SHEU2011 provides energy use per square meter floor area values for different building types and various age brackets. This dataset is only for residential buildings however, so for C&I buildings the CEU database was used, although age bracket data was not available. The relevant values are put into key value tables which are then used to look up the energy use for each building according to its use type and age.

The energy use of each building is calculated based on footprint area, number of storeys, and the relevant energy use per square meter value for the use type. These three numbers are multiplied together to get

the total energy use per year for each building. This can then be summed or averaged for the dataset as a whole or by DA.

There was a significant amount of data cleaning that needed to be performed for the different datasets, particularly the city database. This included checking for and removing erroneous values and entries as well checking that the values were listed in the correct units. Some buildings had multiple listings, so the duplicates needed to be removed. Buildings labeled as strata had numerous problems including no differentiation between commercial and residential stratas, as well as many erroneous buildings that didn't exist or were actually vacant land. Properties with multiple buildings were listed as strata under use type, however most of these turned out to be detached garages. To prevent the entries from skewing the results they were removed and added as additional "garage" fields associated with the larger building on the property. After this the city database was cross referenced with the seismic database, and all entries that did not correctly cross reference were removed after spot checking confirmed that they were erroneous.

The bottom up statistical methodology employed here combined with the cross-referenced data from the different datasets tied to geographical coordinates allows for interesting analysis and visualizations to be obtained that could not be achieved using conventional analysis. One example is getting spatially resolved breakdowns of the energy use of the building stock across multiple dimensions such as age, use type, and location (neighbourhood/DA). Plots of these parameters can be overlaid onto maps of Victoria, so it can be clearly seen which areas have older buildings or greater energy demand. Additionally, since most of the data is building-level there is no need to assume certain distributions of parameters such as building age. This eliminates much of the guesswork needed in statistical models, and allows the model to be more accurate.

4. Results

This building stock model is useful for creating visualizations using GIS, since all building information is tied to geographic coordinates. As a result, building density, energy use and energy use per capita can be plotted using heat maps overlaid on the city map and DAs. This can be very useful for policy makers and city planners, because they can easily see areas of high energy use, allowing targeted policies to be developed. Figure 4 shows estimates of building energy use according to the building stock model. The lighter blue circles indicate lower energy use, and the darker blue indicate higher energy use. Due to the high number of lower energy use buildings (single detached houses) the colour scale is not linear but rather quantile, i.e. each category has the same number of buildings in it. This is necessary due to the high extremes of energy use of large towers or malls.

Figure 5 above shows the same building energy plot as Figure 4 zoomed in to individual building level and showing the DA boundaries so that the variety of energy use in different DAs can be seen.

Figure 6 shows the effective age distribution of the building stock. Effective age is the age that is representative of the current state of the building. For example, a building could be built in 1950, however it was renovated in 1980, so it's effective age is 1980 because it is assumed that things like increased insulation and structural improvements have been made. It can be seen that there are certain areas where there are more older buildings, and others more newer ones. Red dots indicate old buildings (pre-1900), blue dots indicate recent ones (post 2010), and light green and yellow indicate middle values (1960-1970).

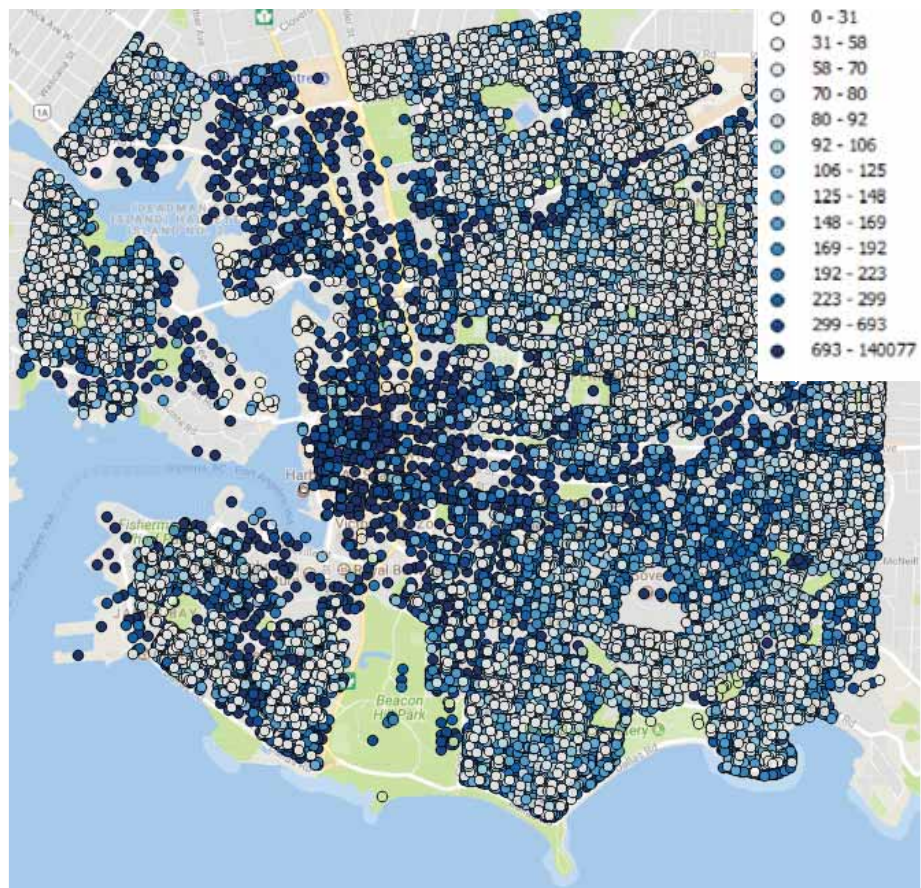


Fig. 4: Map of building energy use of City of Victoria.



Fig.5: Zoomed in portion of Fig 4 plot, but with the DA layer turned on showing their boundaries.

In this way the building stock model can help determine if policies and incentives should be targeted not only to certain spatial areas, but also building use types or ages.

Figure 7 above shows the total energy use and per capita energy use for each DA. Some are much higher than others, typically indicating either a higher density or more commercial buildings with few residential buildings. It can be seen that per capita use tends to follow the total energy use, implying that density is the major determinant of energy use. However, there are some exceptions that have dramatically different total and per capita values. This could be a good indicator to examine these specific DAs in more detail to see if there are reasons for this.

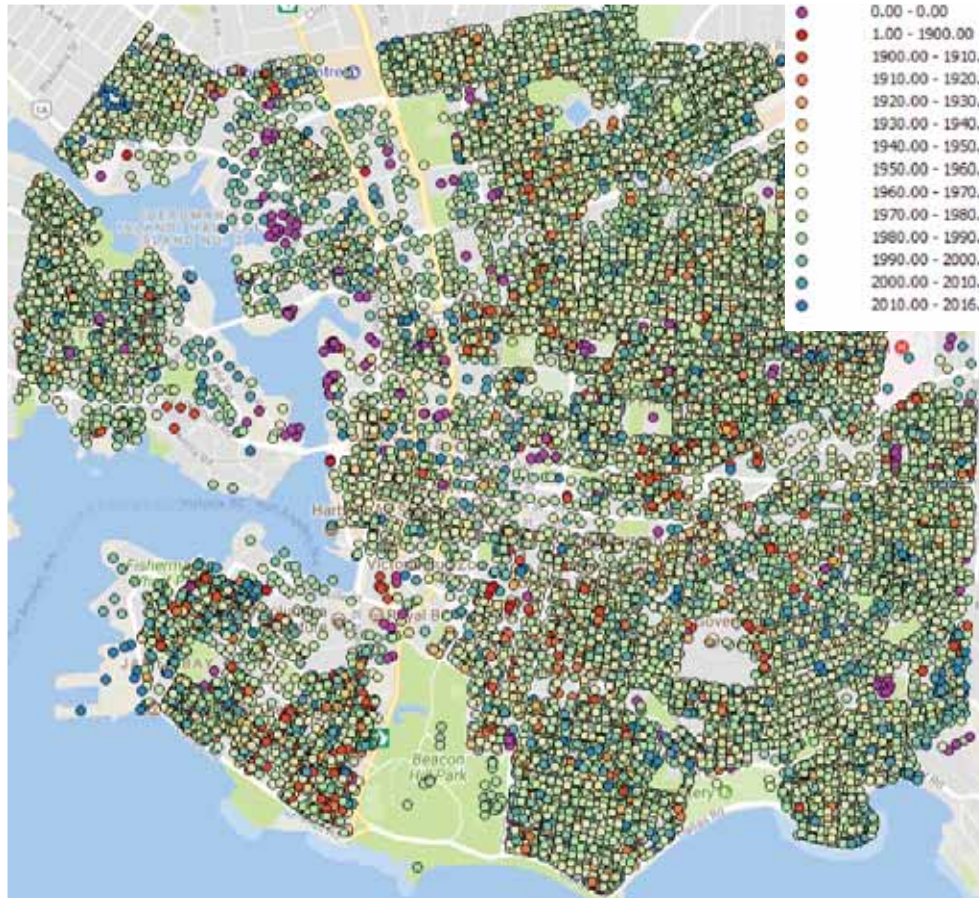


Fig. 6: GIS plot of effective building age. Purple dots indicate buildings that do not have age values recorded

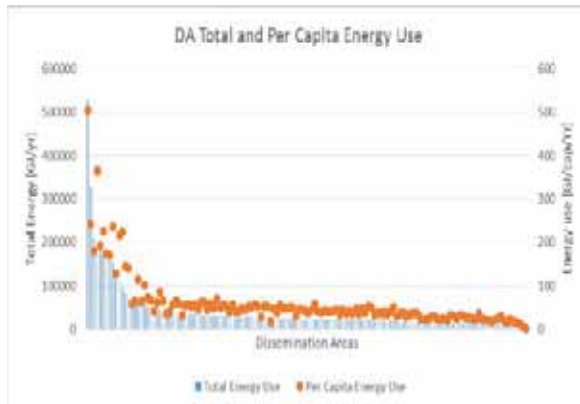


Fig. 7: Plot of the total and per capita energy use for all dissemination areas

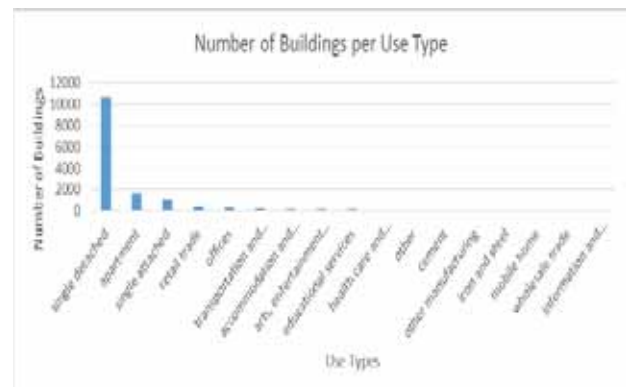


Fig. 8: Plot showing the number of buildings for each building use type for the whole city

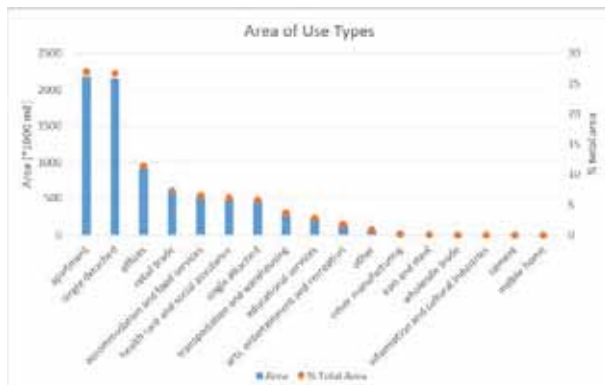


Fig. 9: Plot showing the floor area for each building use type for the whole city.

Figure 8 and Figure 9 above show some specific use type data for the whole city. Figure 8 clearly shows that single family homes make up the majority of the number of buildings. However, Figure 9 shows that in terms of floor area, apartments and single detached homes have almost the same amounts, at just over 26% of total floor area each.

Figure 10 shows the percentage of total energy used by each use type. Single detached homes and apartments consumed the most energy, followed by accommodation and food services, then offices.

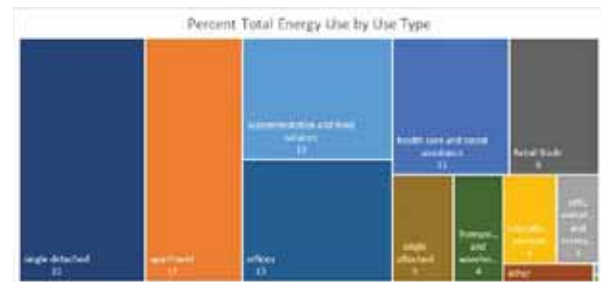


Fig 10: Percent of total energy used by each use type.

Figure 11 breaks down the total residential energy use into the three residential use types, as well as their effective age brackets. As can be seen there is a large proportion of the energy use in buildings with effective built ages of between 1960 and 1980.

5. Discussions

The results of a detailed analysis of the building stock model can have many implications for city planners and policy-makers. The usefulness to planners when developing policy to reduce the city's carbon emissions is significant. It allows policy makers to visually see certain areas or attributes that can be targeted to reduce emissions that may not otherwise be apparent. Certain areas may have a higher energy consumption than others, or perhaps buildings constructed in a.

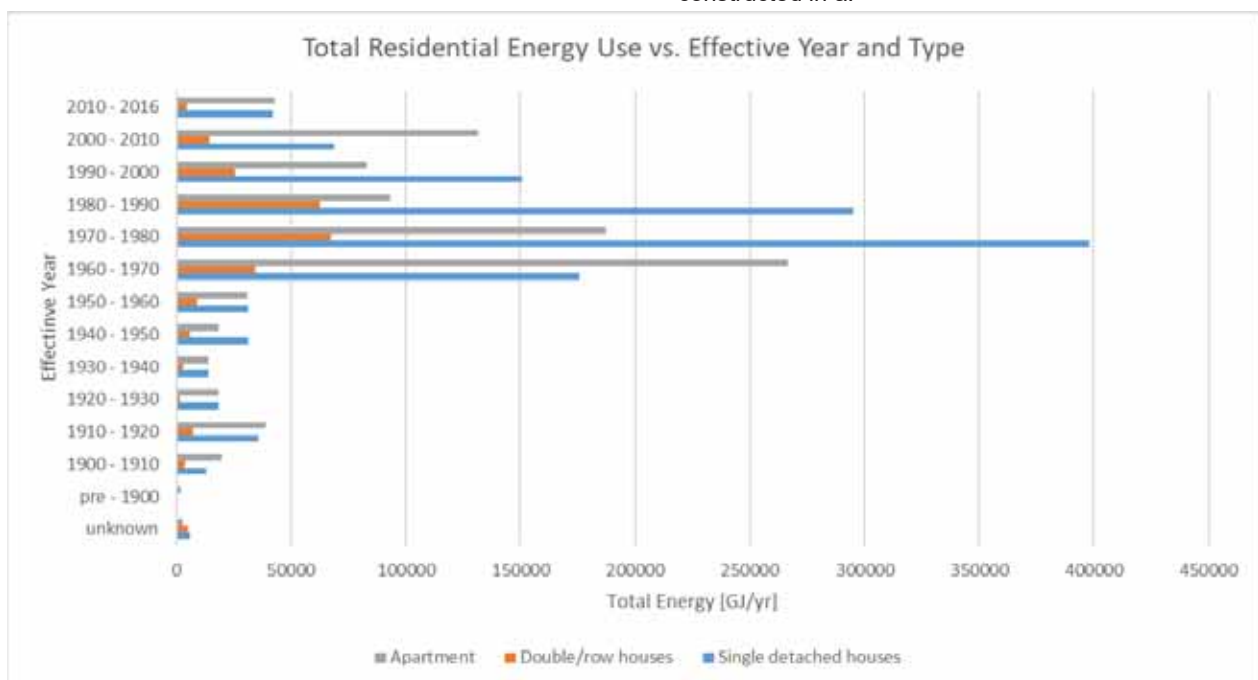


Fig 11xxxxx: Total Residential Energy Use values for the City based on effective year and type.

certain decade may perform worse than expected and so should be targeted over those from other decades.

The building stock model also serves as a platform on which to add more data as it becomes available. An obvious case would be more detailed building information such as heating system details, heating fuel type and other building envelope details. This would allow for the effects of energy retrofits to be assessed. Energy retrofit datasets exist, however they have often been anonymized to protect property owner's identities. However, if these could somehow be linked to spatial stock models like these then retrofit incentives could also be analysed in greater detail.

The spatial aspect would also be useful in assessing the potential for district heating systems and electrical microgrids. Since the dataset is viewable in GIS, it is simple to look for areas of high demand density that could make district heating economically viable.

6. Conclusions and outlook

Building stock models are useful to municipalities in deciding how to develop policies to reach their climate change goals. A bottom up statistical building stock model was developed for the City of Victoria using data from a variety of data sources. The building entries include information such as use type, height, footprint area, number of storeys, and geographical coordinates. Energy use for each building was determined using per square meter energy use values from two NRCan sources.

This dataset can be used with GIS software to create spatially accurate assessments and to graphically show various parameters such as energy use density, building age and building use type. This is useful to quickly see certain areas where there may be problems or that may be performing well. With a building stock model, municipalities can develop policy that can be more targeted and hopefully more effective.

7. Next Steps

Some further investigation and analysis steps that could usefully be performed in the future include the following.

Updating building footprints, heights, and geographical coordinates using updated LIDAR data from May 2017 would reflect the increases in the number of buildings as well as other changes and replacements in the building stock.

Integrating more detailed building specific data (heating system type, envelope R values, window

types, etc.) and energy retrofit information would allow a more in-depth study and higher accuracy modelling energy consumption and emissions information. It would also allow an exploration of retrofit options and incentives and estimating the energy and emissions reduction potential.

Using more specific energy data if or when it becomes available could also help improve the model accuracy. Most of the energy data used comes from NRCan studies that are aggregated at the provincial level. If energy use data for different building types and ages could be obtained at a smaller scale, such as for Vancouver Island, then more accurate estimates could be produced. The climate of the south west coast of British Columbia is very different from the rest of the province, so it is important to capture these variations.

Obtaining industrial energy use per square meter values for the major industries in Victoria so that they can be added into the model would better represent energy use in this sector.

More broadly, a move to time series data so that higher fidelity models could be made that look at hourly trends instead of annual averages. This would allow a much better analysis of renewable energy employment challenges, which revolve around the matching of demands and supplies.

Finally, the use of building energy simulation tools such as EnergyPlus has the potential to give highly detailed information on the energy use of specific buildings. A comparison between modelling typical buildings in EnergyPlus (a more engineering-based approach) and this statistical approach would be highly informative. This would provide time-series information, and would also allow the impact of specific interventions to be predicted more accurately. This could also be combined with an optimization algorithm as in [8] to explore the most cost-effective ways of improving the Victoria building stock.

Acknowledgements

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Roadmap to Resilient, Ultra Low Energy Buildings in the Pacific Northwest

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Abstract

Ten Canadian and US jurisdictions are working together through the Pacific NorthWest Economic Region (PNWER) to develop a policy and technical "Roadmap" to achieve optimized performance in new and existing buildings by 2030. This includes deep energy retrofits of existing buildings and net-zero energy ready new construction, while "future proofing" buildings to improve their resilience to climate change. This paper summarizes performance improvements sought for the building stock of PNWER jurisdictions, including:

- Minimizing energy consumption (quantitative);
- Minimizing on-site GHG emissions and those from electricity generation (quantitative); and,
- Reducing vulnerability to climate change and enhancing durability and comfort (qualitative).

It describes related building design practices for new construction and alterations to existing buildings, based on analysis of case study buildings throughout the Pacific Northwest. It presents results of energy and GHG reduction potential and comments on the potential for such measures to be aligned with climate change resilience.

Finally, the paper provides a balanced scorecard framework for evaluating government policy measures to address market barriers and achieve the desired civil engineering performance objectives.

The conclusion provides a summary of key findings that could inform the future content of the "Roadmap" which would supplement jurisdiction specific technical analysis and policy development that responds to the unique circumstances of each Province, Territory, or State.

Keywords:

Energy efficient buildings, climate change mitigation, adaptation, buildings policy.

1. Introduction – PNWER Roadmap

Buildings in the Pacific Northwest account for a considerable proportion of total energy consumption and greenhouse gas emissions and are thus, a focal point for provincial, state, and territorial (P/S/T) policymakers to improve affordability and facilitate climate change mitigation and adaptation measures.

The Pacific NorthWest Economic Region (PNWER) is a statutory public/private non-profit created in 1991 by the states of Alaska, Idaho, Oregon, Montana, Washington, and the Canadian provinces of British Columbia, Alberta, Saskatchewan, and the Yukon and Northwest Territories. PNWER's goals include coordinating government policies throughout the region, identifying and promoting "models of success", enhancing the competitiveness of the region in both domestic and international markets, and achieving continued economic growth while stewarding environmental protection.

Since 2014, PNWER has conducted research to promote energy efficiency in new and existing buildings across the region by:

- Preparing case studies of deep energy retrofits and net-zero energy ready construction (best practices);

- Conducting analysis of regional impact potential, in particular energy and emission reductions, by fuel and building type;
- Reviewing P/S/T policies, legislation, and market mechanisms to expand market uptake of best practices;
- Facilitating dialogue between the building design community (e.g. engineering associations), energy companies, education institutions, financiers, and policymakers on opportunities and constraints; and,
- Mapping potential pathways to achieve universal market transformation over the coming decade.

Ultimately, PNWER aims to prepare a formal "Roadmap" for P/S/T legislators and private sector leaders to review and potentially use as a template for preparing policy and market mechanisms that facilitate resilient, ultra-low energy buildings. The Roadmap will address key policy drivers such as improving energy affordability, increasing investment in the existing building stock, "future proofing" buildings to be resilient to changes in climate and potential disasters such as seismic events, and mitigating GHG emissions.

2. Addressing Energy Use and Greenhouse Gas Emissions in Buildings – Case Studies

Table 1 illustrates the best practice case studies that were reviewed as part of the analysis for this project. They include new construction of ultra-low energy buildings and major alterations to existing buildings, also referred to as “deep energy retrofits”. Project selection criteria included: access to at least two years of measured energy dataⁱ, completion of a survey by the project owner or design professional, and access to information on key design innovations. Projects from all ten of the P/S/T jurisdictions have been included, along with two projects outside of PNWER to broaden design solutions.

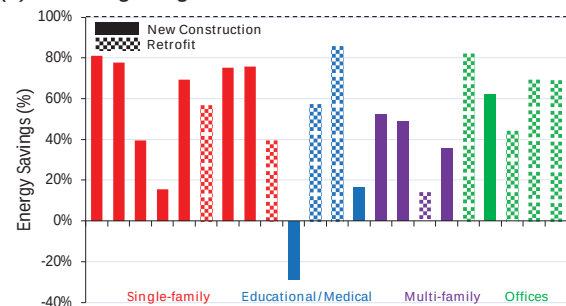
Table 1: PNWER Best Practice Case Studies

CASE STUDY BUILDING INFORMATION				
NEW /RETROFIT	LOCATION	REGION	CLIMATE ZONE ⁱⁱ	YEAR COMPLETED
Single Family Dwellings (Houses)				
New	Regina	SK	7	2007
	Red Deer	AB	7	2008
	Haines Junction	YK	8	2013
	Inuvik	NWT	8	2013
	Burnaby	BC	5C	2013
	Dillingham	AK	8	2012
	Fairhope	AL	2A	2013
Retrofit	Vancouver	BC	5C	2014
	Boise	ID	6B	2011
Educational/Medical Buildings				
New	Seattle	WA	4C	2011
	Portland	OR	4C	2014
Retrofit	Hood River	OR	5B	2010
	Dillingham	AK	8	2014
Multi-Unit Residential Buildings (MURBs)				
New	Issaquah	WA	4C	2012
	Whitehorse	YK	8	2010
	Waterloo	ON	6A	2006
Retrofit	Vancouver	BC	5C	2012
Office Buildings				
New	Seattle	WA	4C	2013
Retrofit	Salem	OR	4C	2010
	Billings	MT	6B	2006
	Bremerton	WA	4C	2011
	Priest River	ID	6B	2009

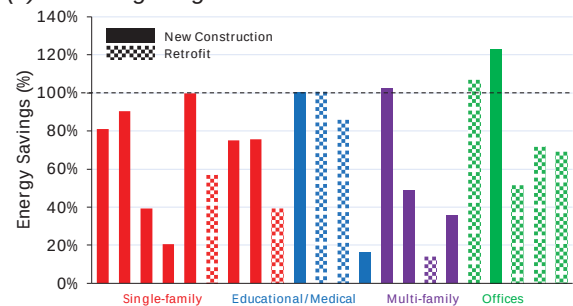
Actual energy consumption data of case studies was compared to baseline energy performance benchmarks for each building typeⁱⁱⁱ, construction type (new construction versus existing building alterations), and region to determine the absolute and relative energy performance improvement in kWh/m² (or kBtu/ft²) and percentage below baseline. On-site generation of renewable energy (e.g., photovoltaics) was separated from energy end-use for improvements. Figure 1 illustrates the energy savings for the case studies as a percentage of the baseline.

Figure 1: Percent Energy Savings Compared to Baseline

(a) Including PV generation



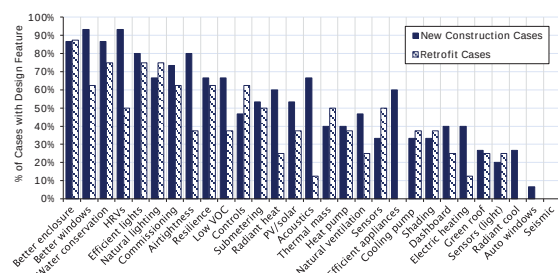
(b) Excluding PV generation



The average greenhouse gas emission reduction for the case studies across all sectors was 70% relative to their baselines^{iv}, illustrating achievement near the target of an 80% reduction in GHG emissions below 2007 levels by 2050^v.

Figure 2 highlights energy efficiency design features that often differ from common construction practices, along with the proportion of case studies that included each design feature. This categorization can help to inform which technologies and design practices the Roadmap could focus on; to facilitate market awareness and acceptance, product availability, and industry capacity building.

Figure 2: Common Design Features



The top five most common high performance design features were:

- High performance building enclosures;
- High performance windows;
- Water conservation;
- Heat recovery ventilation; and,
- Efficient light fixtures and bulbs.

It is recommended that a separate “market readiness scan” be prepared on each of those design features, specific to the PNWER region.

Surveys of owners and/or design professionals revealed non-energy benefits and included, but were not limited to:

- Improved resilience to extreme weather events such as rain, wind, drought, and temperature.
- Water conservation.
- Reduced sound transmission into buildings.
- Improved occupant comfort.
- Reduced solar gains that damage furniture and interior building components.
- Neighbourhood revitalization.
- Indoor environmental quality considerations through continuous fresh air coupled with heat recovery ventilators and low VOC materials.

While some of these non-energy benefits are often not quantifiable in a manner that can be compared between buildings, it is possible to conduct qualitative analysis on the extent to which a policy or project supports such benefits. Furthermore, anecdotal evidence suggests that market willingness to pay for such benefits is a critical driver for investment in high performance buildings.

3. Qualitative Assessment of Resiliency

Resilience is defined as the ability to prepare and plan for, absorb, recover from, or more successfully adapt to actual or potential adverse events^{vi}. With the realities of climate change, yielding shifting climate norms and increased intensity and frequency of weather events, resilient design is imperative to ensure long-term viability of buildings and communities. Resilience initiatives focused on adjusting to climate change is known as climate adaptation.

Recent studies in building resilience show advantageous returns on capital investments for resilient design. The Multihazard Mitigation Council (2017) shows returns between \$4 to \$6 for every \$1 spent on building hazard mitigation. The financial case for preventive disaster resilience planning is strong, particularly when considering the non-monetary benefits of reduced cost of human life and minimized community disruption.

The climate projections for the PNWER region vary significantly due to the large geographical area encompassed by the organization. The Pacific Climate Impacts Consortium’s (PCIC) Regional Analysis Tool permits plotting climate model projections for precipitation and the maximum temperatures over the greater extent of the PNWER region on an approximately 100x100km scale, shown in Figure 3 and Figure 4, respectively. Due to the scale, these models have insufficient temporal or spatial resolution to infer statistical weather distributions, but does provide insight into general climate trends out to the year 2080 as a relative percent change to the 1961-1990 baseline values.

The Representative Concentration Pathway (RCP) 8.5 W/m² from the Coupled Model Intercomparison Project 5 (CMIP5), the “status quo” climate model projections, are used for this paper.

Figure 3: CMIP 5 RCP8.5 2080 Summer Precipitation Percent Change relative to 1961-1990 Baseline

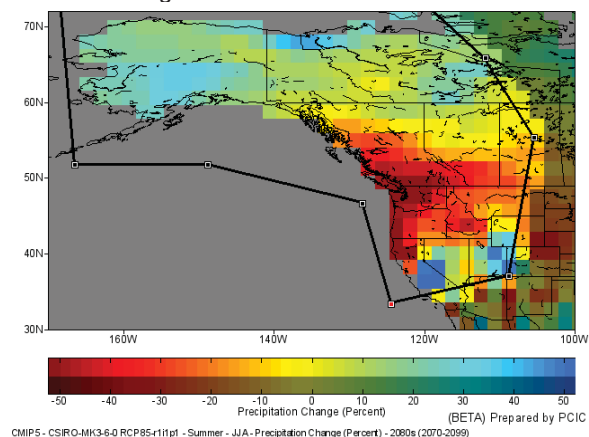
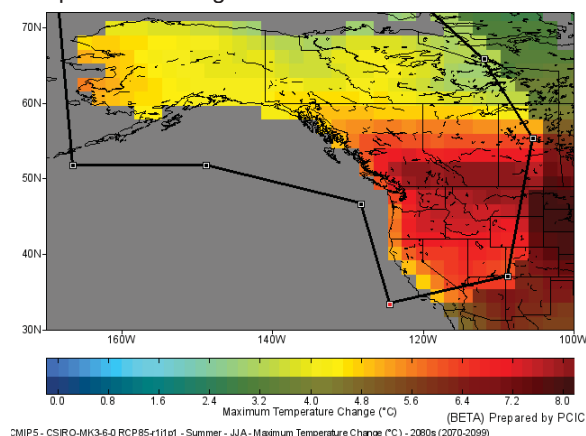


Figure 4: CMIP 5 RCP8.5 2080 Summer Maximum Temperature Change Relative to 1961-1990 Baseline



The consensus on climate change effects within the region are an increase in overall seasonal temperatures and increase in extreme weather events. This leads to more extreme precipitation, leading to flood risks and wind damage, and significantly reduced summer time precipitation, leading to droughts, hyperactive fire seasons, and water shortages. Consequently, climate change Adaptation and Mitigation Measures (AMMs) which focus on minimizing the effects of heat transfer through the building enclosure, design for flooding and water conservation, more intense wind activity, and decentralized energy production systems are anticipated to see increased usage in resilient design.

The top 5 common ECMs identified demonstrate that a focus on energy efficiency is not necessarily aligned with climate adaptation or mitigation strategies, however significant overlap does occur. With higher summer outdoor sensible dry bulb temperatures, the use of low solar heat gain windows, solar shading, and high R-value walls will assist heat pumps in providing air conditioning for the greater parts of the region.

The process for resilient design is to first conduct a vulnerability assessment, which identifies climate loading and their potential effects on the building system. Thereafter, identifications of AMMs that resolve the root causes of the vulnerability is required, and the subsequent adoption of these retrofit measures. Ideally, these AMMs would be aligned with energy efficiency and emission reduction measures. Significant cost-savings can be found by concurrently introducing AMMs with planned renewals for existing buildings, or, for new construction, by following Integrated Design Process that includes building enclosure, structural, and mechanical specialists, in conjunction with climate risk assessment experts.

4. Aggregated Regional Impact Analysis

RDH performed an extrapolation of impact of phased-in energy targets, as determined from the PNWER Roadmap case studies, to the construction of new buildings and retrofits of existing buildings forecasted to occur from 2017 through 2046. The extrapolation provided an estimate of the annual electricity, natural gas, and GHG emissions savings compared to the baseline for a 30-year time horizon through to 2046. The analysis concluded at the 2046 time horizon but the benefits are expected to continue farther into the future. The analysis is limited to those building types included in the original case study review but could be extended to the remaining building stock following a similar approach.

This work served to illustrate the “size of the prize” that could result from new government policy and market mechanisms. The specific outcomes depend on the assumed levels of energy savings and rate of implementation. The aggregated regional impact analysis will continue to be refined as project partners and references bring new data to the table.

A business-as-usual baseline was compared to the potential from a phased-in policy implementation to bring energy consumption from new and existing buildings to higher performance targets represented by case study buildings from the PNWER in previous phases of this work. The two scenarios assumed identical new construction and retrofit rates (discussed below). The Roadmap policy scenario assumed that the improved energy efficiency would be applied to a fraction of the buildings scheduled for new construction and retrofit based on the three tiers of implementation. The three tiers of implementation modeled assumed:

- One-third of new construction and one third of buildings scheduled for retrofit would achieve energy performance represented by the case studies, implemented in construction during the period between 2020 and 2024,
- An additional one-third from 2025 to 2029; and,
- All buildings achieve performance levels represented by case study building in 2030 and beyond.

The methodology of estimating the energy and GHG emissions savings from the potential policy implementation included the following steps.

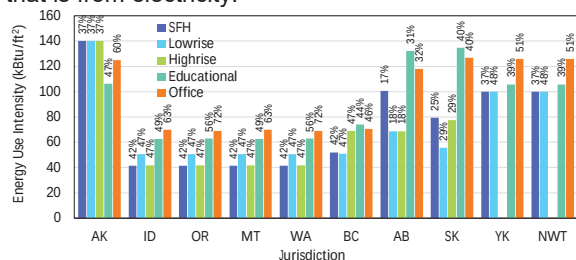
Estimate of Building Energy Use Intensity

The energy use of existing buildings, retrofitted buildings (both those subject to policy measures and those not), and new construction (both those subject to policy measures and those not) were estimated in each jurisdiction.

The baseline (non-intervention) energy use intensity for existing buildings was estimated from public

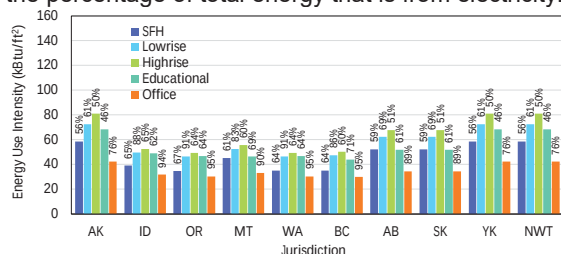
sources with the majority of data from national energy use surveys in Canada and the United States^{vii}. The estimated energy use intensity (EUI) for existing buildings is shown in Figure 5. The data labels represent the percentage of total energy use that is from electricity.

Figure 5: Baseline existing building total energy use intensity. Labels indicate the percentage of total energy that is from electricity.



The EUI for the new building baseline was estimated from the US Department of Energy Commercial and Residential Building Prototype models^{viii} for cities with representative climate zones for each jurisdiction. The assumed compliance code version was ASHRAE 90.1-2013 for commercial buildings and 2012 IECC for residential buildings. The EUI for new construction is shown in Figure 6. The data labels represent the percentage of total energy use that is from electricity.

Figure 6: Baseline new construction total energy use intensity for year 1 of extrapolation. Data from ASHRAE 90.1-2013 and 2012 IECC. Labels indicate the percentage of total energy that is from electricity.



The baseline new building energy use intensity was assumed to improve throughout the extrapolation period to account for a natural progression of improvements to building codes and energy efficiency requirements. The amount of improvement was estimated as 1.5% per year^{ix} over the starting baseline EUI.

The improvement in energy use intensity of buildings was assumed to be based on a percentage savings for the building types from the case study buildings in the earlier tasks of the PNWER Roadmap. The assumed savings over retrofitted existing buildings was 50% all building types. All buildings that were retrofitted but not under the policy measures were assumed to save 10%^x compared to the baseline as a conservative representation of a “common practice” retrofit. The

assumed savings for new buildings was 60% for single family homes and 35% for all other building types. All savings due to the policy measures were assumed to apply equally (as a percent) to natural gas and electricity consumption. The energy consumption for buildings meeting the roadmap target are assumed to remain constant over the extrapolation period.

Building Floor Area

The extrapolation required information of the total building floor area as well as the amount of area for retrofits (both those aligned with best practices and those common practices that do not) and new construction in each year.

The existing floor area at the start of the extrapolation period (2017) for each building type in each PNWER jurisdiction was estimated from national level statistical data such as CBECS, RECS, SCIEU, and SHEU. Sufficient data is not generally available in these databases to identify individual jurisdictions but rather is presented by census area. In this case the building floor area was assumed to be proportional to the population. An example of this weighting method is that Idaho accounts for ~7% of the population in US Census Division 8 (Mountain) therefore it was assumed that Idaho contains 7% of the built floor area in Division 8. A summary of the floor area for each building type in each jurisdiction at the start of the extrapolation period is shown in Table 2.

Table 2: Total 2017 Existing Building Floor Area per Jurisdiction used in the Extrapolation (millions ft²)

Jurisdiction	SFH	Low-Rise	High-Rise	Educational	Office
AK	348	16	37	16	37
ID	772	35	83	63	69
OR	1,875	84	201	84	201
MT	483	22	52	40	43
WA	3,334	150	357	149	358
BC	2,886	312	132	117	207
AB	2,751	218	117	104	184
SK	654	50	32	28	50
YK	25	2	-	1	2
NWT	29	2	-	1	2

The annual new construction and retrofit rates were estimated as a % of existing building stock from available public data. The same rates were applied to all jurisdictions. An estimate for new construction rates was determined from changes in floor area indicated in national building reports^{xi}.

The annual retrofit rate was similarly estimated from available sources. The retrofit rate for commercial buildings was assumed to be 2% per year^{xii}. The retrofit rate for single family homes was assumed to be 1% per year^{xiii}.

The annual square footage of floor area of applicable construction for each building type was then estimated

by multiplying the total floor area of each building type in each PNWER jurisdiction by the annual new construction and retrofit rates, respectively.

The annual energy use from the building types included in this study was then predicted under both the roadmap scenario and the current baseline scenario. The savings from following the roadmap was calculated as the difference between the two scenarios. The annual savings was extrapolated over the 30-yr time horizon to estimate cumulative annual savings in key years.

Reduction in Greenhouse Gas Emissions was also estimated based on local emissions factors for electricity shown in Table 3. The emissions factor for natural gas was assumed to be 0.18 kg/kWh for all jurisdictions. The analysis does not account for potential future changes to the emissions factor from electricity grids as these are not known.

Table 3: GHG Emissions Factors from Electricity use

Jurisdiction	Emissions (kg CO ₂ e per kWh)
AK	0.50
ID	0.05
OR	0.12
MT	0.59
WA	0.06
BC	0.01

Results

The estimated total energy use from the building stock for the baseline conditions is shown in Figure 7. The corresponding GHG emissions are shown in Figure 8. The extrapolation shows a continued increase in both energy consumption and GHG emissions from the building sector due to the expected increase in building area from new construction in the next 30 years. The results emphasize the significance of the single family home segment of the building stock on both energy consumption and GHG emissions

Figure 7: Extrapolated annual energy consumption by building type throughout the study timeline for the baseline scenario

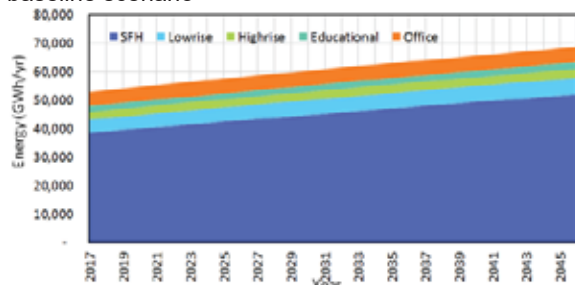
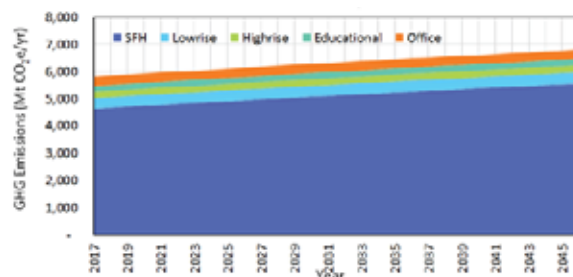


Figure 8: Extrapolated annual GHG emissions by building type throughout the study timeline for the baseline scenario



Total energy use from the building stock for the Roadmap policy conditions is shown in Figure 9. The corresponding GHG emissions are shown in Figure 10. Under the policy scenario the energy consumption and GHG emissions continue to increase in the initial years due to the gradual implementation of the policy starting in 2020. The energy and emission increases are eventually curbed as shown at the inflection point in Figures 9 and 10. This represents a potential “turning of the corner” at which point the building stock continues to increase but the energy and emissions impact starts to decline. By the end of the 30-year time horizon of the analysis, there is a modest decrease in energy consumption and emissions relative to the starting year of the analysis (2017). Despite the modelled policy intervention, the single family home segment continues to have a significant impact on the entire region and has the potential for increased reduction if alternate policy approaches or scenarios are implemented.

Figure 9: Extrapolated annual energy consumption by building type throughout the study timeline for the Roadmap policy scenario

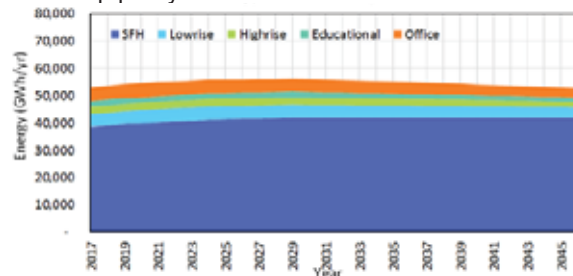
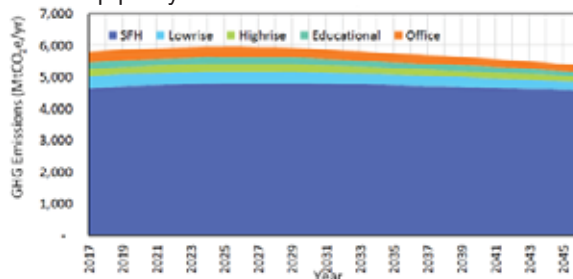


Figure 10: Extrapolated annual GHG emissions by building type throughout the study timeline for the Roadmap policy scenario



The percent savings of the Roadmap policy scenario versus the business as usual baseline is shown in Figure 11 (energy) and Figure 12 (GHG). The policy

scenario shows savings in all segments with significant improvements in the commercial buildings.

Figure 11: Percent annual energy savings from implementing the Roadmap scenario compared to baseline

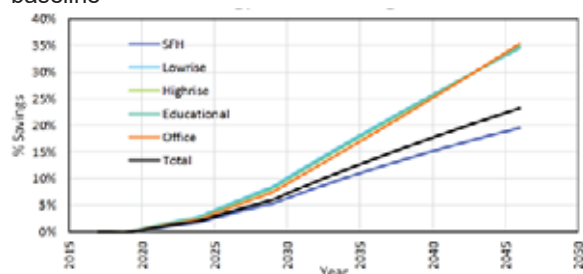


Figure 12: Percent annual GHG emissions reduction from implementing the Roadmap scenario compared to baseline

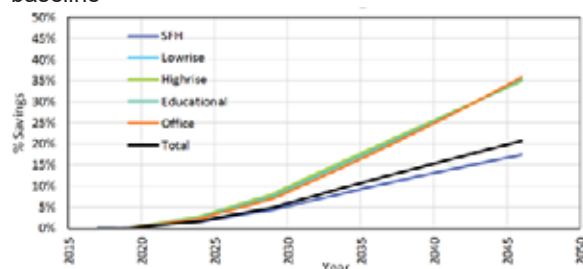


Table 4 summarizes the “size of the prize”, in other words, the potential energy savings and emission reductions that could be achieved in the PNWER region, resulting from improved construction practices that are facilitated through new government policies and market mechanisms.

Table 4: Aggregated Estimated PNWER Benefits

Year		2025	2035	2046 (30yr)
Energy Savings	GWh/yr	8,582	41,069	83,031
	%	2%	11%	19%
Electricity Savings	GWh/yr	4,440	20,703	40,720
	%	3%	13%	22%
Natural Gas Savings	GWh/yr	4,142	20,366	42,311
	%	2%	9%	18%
GHG Savings	MT/yr	1,863	8,855	17,769
	%	3%	11%	20%

This applies to current construction forecasts, and does not envision an accelerated schedule of building retrofits beyond the 1-2% per year. However, government policies could, in fact, accelerate the building alteration rate given sufficient market stimulus, the subject of future research. Furthermore, the full phase-in of the energy performance targets is assumed to be 2030; but again, government policy could phase in full implementation sooner. Many alternate policy approaches or levers could be modelled in a similar manner to determine the most appropriate or impactful approach to take in attempting to reduce regional energy consumption and emissions attributable to the building sector.

5. Framework for Policy and Market Measures

The aforementioned analysis illustrates that policy and legislative interventions by provincial, state and territorial governments in PNWER could facilitate an approximate 20% reduction in the overall energy use and emissions of the building stock under the scenario presented. Government policy measures can often work in tandem with market driven measures that promote non-regulatory leadership. For the purposes of this paper, these are collectively referred to as “policy measures” and include, but are not limited to:

- Strategic planning
- Public education and engagement
- Coordination
- Research, development, demonstration
- Industry training and capacity building
- Voluntary adoption of advanced standards
- Financing
- Market stimulus and incentives
- Regulations

This paper only skims the surface of policy measures and does not define them, nor provide best practices, but rather presents a framework for evaluation.

Policy measures are justified on the basis of achieving public interest objectives such as;

- First cost affordability and incremental capital cost of performance improvements – quantitative (\$/m² and % increase in capital cost);
- Financial value of energy saving and carbon pricing benefits to consumers – quantitative (annual \$/m² and % reduction in costs);
- Live-cycle affordability and internal return on investment (IRR) for consumers (%);
- Cost of delivery of policy measure (to energy utility, government department or industry association) – quantitative (\$/year);
- Non-energy benefits – quantitative (% of energy benefits, translating to \$/m²);
- Mitigation benefits (annual GHG tonnes/yr);
- Resiliency benefits – qualitative (rating); and,
- Macroeconomic benefits – quantitative (GDP growth, person-years employment per \$ invested).

Each jurisdiction will have its own political, social, economic and environmental drivers to advance policy measures and as such, will be able to “weight” the aforementioned objectives on their relative importance. Furthermore, with an independent evaluation of policy measures a “rating” can be assigned to each of the aforementioned measures, reflecting their relative impact.

The table below provides a sample framework to illustrate a “balanced scorecard” evaluation of policy

measures. The nine policy measures are all “rated” with a score of between 0 and 10, depending on their relative impact on achieving each of the eight objectives. The objectives are all weighted to reflect the circumstances of the jurisdiction (how important is GHG reduction versus job creation and consumer affordability). The column on the right would include a score out of 1,000, enabling a prioritization of policy measures subject to limited human and financial resources to implement them.

Table 5: Sample Policy Evaluation Framework

	Objectives (8 in total)								
Weighting (/100)	10	10	15	15	15	10	15	10	
Policy Measures	Ratings (/10)								Total (/1000)
1	#	#	#	#	#	#	#	#	###
2	#	#	#	#	#	#	#	#	###
3	#	#	#	#	#	#	#	#	###
4	#	#	#	#	#	#	#	#	###
5	#	#	#	#	#	#	#	#	###
6	#	#	#	#	#	#	#	#	###
7	#	#	#	#	#	#	#	#	###
8	#	#	#	#	#	#	#	#	###
9	#	#	#	#	#	#	#	#	###

6. Conclusions and Outlook

The work to date on a Roadmap to Resilient, Low Energy Buildings in the Pacific NorthWest Economic Region (PNWER) has highlighted examples of how the building sector, both new and existing, can be improved with resultant economic and environmental benefits. Extrapolation efforts have shown the significant potential for impactful change within the region should policies be enacted to improve energy efficiency and resilience. The Roadmap development will continue with additional analysis but the results to date have highlighted preliminary conclusions including:

- Case studies provide valuable insight into successful pathways to near net-zero energy buildings in the Pacific Northwest. Barriers to high performance construction and retrofits can be lowered by learning from these cases. Projects that have undertaken these initiatives have saved an average of 72% in energy consumption and 70% in greenhouse gas emissions.
- Climate change predictions indicate that the PNWER will experience more frequent and more severe extreme weather events in the coming years. The current emphasis on energy efficiency provides some overlap with improving resilience but more emphasis on design features meant specifically to mitigate the impacts of these events could improve resilience throughout the region while also providing non-energy benefits to building owners and occupants.

- Implementation of a policy roadmap to improve building energy efficiency can result in significant reductions in energy consumption and GHG emissions from the building sector.
- An objective based, “balanced scorecard” evaluation framework could be applied to prioritize one or more diverse policy measures in a manner that reflects the unique circumstances of the jurisdiction and political drivers for legislation.

7. Acknowledgements

The authors would like to thank the BC Ministry of Energy, Mines and Petroleum Resources, the Insulated Concrete Form Manufacturers Association, FortisBC and the Energy Trust of Oregon for financial support and the Pacific NorthWest Economic Region (PNWER) for hosting the project and providing a forum for policy discussion.

8. References (to be completed)

National Academy of Sciences. Disaster Resilience: A National Imperative. Washington, DC: The National Academies Press; 2012.

9. End Notes

i For more than half of the case studies, verified energy data was acquired through: New Buildings Institute. Getting to Zero Database. <https://newbuildings.org/resource/getting-to-zero-database/>

ii Climate zones, as per ASHRAE 90.1 Energy Standard for Buildings, except Low-Rise Residential Buildings.

iii New construction: Pacific Northwest National Lab. DOE Prototype Building Models for ASHRAE 90.1-2013. Existing Buildings. DOE: CBECS (2012), RECS (2015) and NRCAN: SCIEU (2009), SHEU (2011).

iv New construction: Pacific Northwest National Lab. DOE Prototype Building Models for ASHRAE 90.1-2013. Existing Buildings. DOE: CBECS (2012), RECS (2015) and NRCAN: SCIEU (2009), SHEU (2011).

v British Columbia *Greenhouse Gas Reduction Targets Act*.

vi National Academy of Sciences. *Disaster Resilience: A National Imperative*. Washington, DC: The National Academies Press; 2012.

vii Energy use intensity was estimated for most archetypes from the 2014 NRCAN Comprehensive Energy Use Database, 2011 Survey of Household Energy Use, the 2009 Survey of Commercial and Institutional Energy Use, the 2009 Residential Energy Consumption Survey, and the 2012 Commercial Building Energy Consumption Survey. Data was used for each jurisdiction if present. Otherwise, it was assumed to be equal to the regional data (ie. MT and ID used data from the Mountain region).

The data was also supplemented from other sources when available. EUI for the multifamily buildings in BC was taken from the report "Energy Consumption and Conservation in Mid- and High-Rise Residential Buildings in British Columbia" prepared by RDH for BC Housing. Data for schools and offices in Alaska was determined from the report "Energy Efficiency of Public Buildings in Alaska: Metrics and Analysis" prepared by the Cold Climate Housing Research Center. Data for residential buildings in Alaska was taken from the report "2013 Alaska Housing Assessment" prepared by the Cold Climate Housing Research Center.

viii The models were prepared by the Pacific Northwest National Lab (PNNL) and are available online at: <https://www.energycodes.gov/development>

ix The estimate of 1.5% per year was determined by comparison of previous analysis of the energy savings from changes to building codes and energy efficiency standards. PNNL

([https://www.energycodes.gov/sites/default/files/documents/901-](https://www.energycodes.gov/sites/default/files/documents/901-2013_finalCommercialDeterminationQuantitativeAnalysis_TSD.pdf)

[2013_finalCommercialDeterminationQuantitativeAnalysis_TSD.pdf](https://www.energycodes.gov/sites/default/files/documents/901-2013_finalCommercialDeterminationQuantitativeAnalysis_TSD.pdf)) estimated a 7.6% site energy use improvement from ASHRAE 90.1-2013 compared to ASHRAE 90.1-2010 representing ~2.5% per year. Similarly, the Pembina Institute ([https://pics.uvic.ca/sites/default/files/uploads/publications/Pembina-](https://pics.uvic.ca/sites/default/files/uploads/publications/Pembina-Evolution%20of%20Energy%20Efficiency.pdf)

[Evolution%20of%20Energy%20Efficiency.pdf](https://pics.uvic.ca/sites/default/files/uploads/publications/Pembina-Evolution%20of%20Energy%20Efficiency.pdf)) estimated the impact of changes to the British Columbia Building Code and determined a 10% improvement between the 2013 and 2008, ~2% per year. A more conservative 1.5% was applied in this work to reflect the expected challenges in reducing code minimum performance requirements as the energy targets become more stringent.

x Pembina Institute. *Building Energy Retrofit Potential in B.C. Thought Leader Forum* – Vancouver. November 28-29, 2016.

xi Examples include NRCAN's SHEU 2012 which indicates an average floor area increase of ~1.8% per year in Canada between 2000 and 2011 (data from Table 1.2) or the US 2012 CBECS data which indicates an average commercial building floor area increase of ~1.3% per year between 2008 and 2012 (data from Table B1).

xii Olgyay and Seruto, 2010. "Whole-Building Retrofits: A Gateway to Climate Stabilization", ASHRAE Transactions vol 116, part 2, 2010.

xiii Building Energy Retrofit Potential in B.C. Pembina Institute, 2016. <http://www.pembina.org/docs/event/netzeroforum-backgrounder-2016.pdf>

Ready Mixed Concrete Production Using Waste CO₂

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Abstract:

Concrete is the world's most important and most widely used building material. However, cement production is one of the most significant industrial sources of CO₂ emissions. The industry searches for ways to meet increasing demand and reduce the carbon footprint of the concrete produced. One approach is upcycle CO₂ into concrete applications. The beneficial use of carbon dioxide in ready mixed concrete production has been developed and installed as a retrofit technology with industrial users.

The CO₂ utilization approach adds an optimum dose of carbon dioxide to concrete during mixing and batching. The CO₂ can increase the compressive strength of the concrete thereby prompting producers to optimize their mix designs. Testing has shown that 5% cement reductions paired with the carbon dioxide addition can be achieved without compromising compressive strength. The use of carbon dioxide along with a lower cement usage reduces the carbon footprint of concrete without compromising performance.

The potential to pair the concrete industry CO₂ utilization with the cement industry CO₂ production was considered. The capture of cement plant CO₂ is not yet being practiced and implementation barriers exist before it will reach full scale implementation. The scale of CO₂ utilization in a ready mix concrete application mean that a network of producers served by a cement plant could be addressed through a 1 to 2 tpd capture system. Carbon dioxide utilization in concrete production is a viable, synergistic and beneficial approach that can improve the sustainability of the concrete so produced.

Keywords:

Concrete, carbon dioxide utilization, carbon footprint, sustainability

1. Introduction

Concrete is the world's most important building material whose production has steadily increased, remarkably so over in the last 20 years in response to rising demand and infrastructure investment within emerging economies (Figure 1). The annual global cement production was estimated at 4.1 Gt [1] in 2016, or a 246% increase over the output 25 years earlier. The production growth can be illustrated by the report that China consumed 47% more cement between 2011 and 2013 (6.6 Gt) than the United States did during the entire 20th century (4.5 Gt) [2].

Given a generic concrete mix contains about 300 kg cement per cubic meter and a global population of 7.2 billion [3], it can be calculated that around 1.9 m³ of concrete is produced per person, every year. Assuming a density of 2.3 tonnes per cubic meter can allow for an estimated to 4.3 tonnes of concrete produced annually for each person. Concrete is the most abundant man-made material on the planet and, by mass, makes up about 50% of all materials produced globally [4].

Concrete is an incredibly useful and versatile material but its use does have a notable environmental impact. The ever-increasing demand for concrete, combined with the impetus to reduce greenhouse gas emissions, has driven the search for methods to reduce the specific carbon footprint of concrete. The carbon impact of the cement and concrete industry

can be lowered only if the carbon impact can be decoupled from production. Achieving a lower carbon footprint per unit of production is an essential step towards simultaneously increasing concrete output without increasing the cumulative environmental impact.

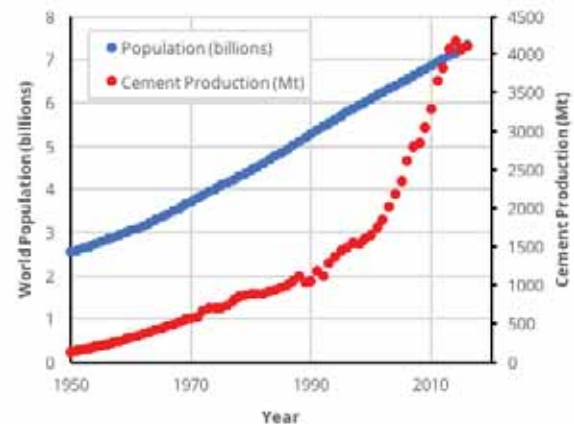


Fig 1: Growth in global cement production and global population (adapted from [1] and [3])

Concrete is considered to be one of the most sustainable construction materials. The embodied CO₂ (kg CO₂/kg material) and embodied energy (MJ/kg material) of concrete is lower than the alternatives that may be considered as replacements [5]. A choice to substitute concrete with an alternative

material would be a choice to increase the carbon footprint. Despite the sustainability advantages that concrete may offer, however, the scale of its use meant that 5.6% of all global CO₂ emissions from fossil fuel and industry in 2015 were associated with cement production [6]. On the product level, about 85% of the carbon emissions associated with concrete are attributable to the cement [7]. Improving the sustainability profile of concrete, by necessity, must focus on the binder.

The concrete industry has long embraced circular production principles. Many waste materials have been beneficially used to make concrete [8–10]. The most impactful and widely used examples are blast furnace slag (a by-product of iron and steel-making), fly ash (a by-product of coal fired power generation), and silica fume (a by-product of silicon metal production). These materials can be diverted from landfills to be beneficially reuse in concrete. The use of waste materials often allows for more efficient usage of cement.

The concrete industry has set goals for producing more sustainable concrete. In 2011, the industry, as lead by the National Ready Mixed Concrete Association, stated a target to improve the carbon footprint of concrete, relative to 2007, by 20% by 2020, and 30% by 2030 [11]. However, the realistic limit to conventional means [12; 13] suggests that new solutions are required.

The idea of carbon dioxide utilization for concrete production has been developed [14; 15]. The use of carbon dioxide to produce concrete potentially connects one industry waste (carbon dioxide) with the industry's main commercial output thereby offering a potentially attractive upcycling solution that works within the principles of a circular economy.

In order for a CO₂ utilization solution to be accepted and adopted by industry it must be readily integrable into existing technologies and production modes. Three different technologies have been developed to allow concrete producers to make more sustainable concrete through the beneficial utilization of waste carbon dioxide. The carbon dioxide utilization concepts involve the reaction of CO₂ with cement in ways that adhere to otherwise conventional production practices. When the carbon dioxide reacts with cement at the earliest stages of hydration there will be the formation of calcium carbonate. The carbon dioxide is stored permanently in the concrete and can impart performance benefits

2. Background

Ready mixed concrete was produced whereby an optimal dose of carbon dioxide was injected into the central mixer during batching. A gas metering system fed a controlled supply of liquid CO₂ through to a discharge conduit. The liquid was converted into a

mixture of CO₂ gas and finely divided solid carbon dioxide particles (commonly referred to as CO₂ "snow") The carbon dioxide was delivered into the fresh concrete whereupon it reacted with the hydrating cement during initial mixing. The concrete was then delivered to the ready mix truck for assessment and testing.

The carbon dioxide undergoes a chemical reaction with the calcium present in the solution phase of fresh, hydrating, concrete (Figure 2). The first step is the start of cement hydration where, upon contact with water, the cement undergoes dissolution and ions (Ca²⁺, SiO₄⁴⁻ and OH⁻) enter solution (Figure 2a). The addition of carbon dioxide snow and gas causes carbon dioxide to go into solution (Figure 2b). First it hydrates to form carbonic acid (H₂CO₃) which then dissociates into the bicarbonate phase (HCO₃⁻) and a proton (H⁺). A further dissociation to the carbonate ion (CO₃²⁻) and a proton. There is an exothermic reaction between the carbonate and calcium ions (Figure 2c). The CaCO₃ product forms in-solution at or near the surface of the hydrating cement. The in-situ creation of calcium carbonate impacts the cement hydration. The typical hydration pathway to form calcium-silicate-hydration gel occurs (Figure 2d). The carbonate product acts as a nanoparticle and can impact hydration seeding or offer pore filling effects.

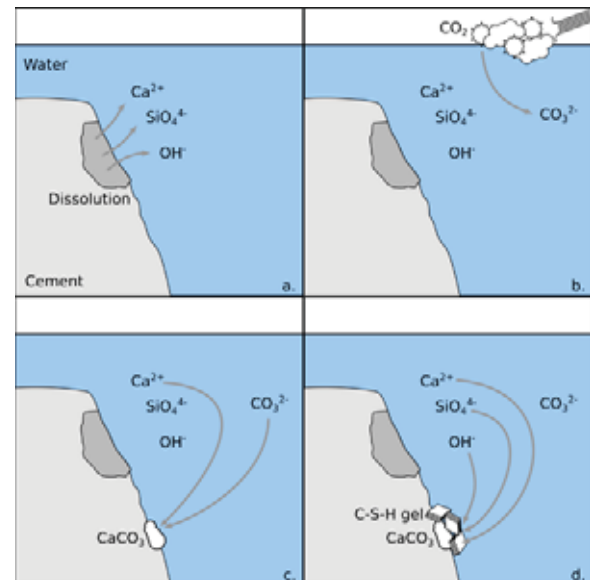


Fig 2: Mechanism of in-situ carbonate formation [16].

Industrial development of the approach established that the carbon dioxide can improve the compressive strength of the concrete [16; 17]. The present study examined whether the improved strength can allow for the mix design to be modified to produce a more sustainable concrete mix. The case of a producer following the approach for one year was examined. Finally, the concept of connecting the waste carbon dioxide produced in cement production with the CO₂ utilization in concrete production was considered.

3. Materials and Methods

A CO₂ injection system was commissioned at an industrial producer. Testing investigated whether the expected compressive strength improvement would allow for the production of concrete with a reduced cement loading. Testing considered two mix designs.

The first was a mix design (H30) with a 30% slag binder. The performance target was 20.7 MPa (3000 psi) at 3 days and 38.0 MPa (5500 psi) at 28 days. A comparison was made between a conventionally produced mix and a batch produced using a CO₂ injection and a mix design with 5% less binder. CO₂ was injected at 0.10% by weight of cement. The water to cementitious ratio was fixed. The baseline mix has a carbon footprint of 424 kg CO_{2e}/m³ concrete according to an Environmental Product Declaration (EPD). The mix design modification reduced the cement by 12.5 kg/m³ and the slag by 5.3 kg/m³.

The second case was a mix design (325P) with a 15% fly ash binder. The performance target was 20.7 MPa (3000 psi) at 28 days. As in the previous case, a comparison was made between a conventionally produced mix and a batch produced using a CO₂ injection and modified mix design with 5% less binder. The water to cementitious ratio was fixed. CO₂ was injected at 0.08% and 0.35% by weight of cement. The baseline mix has a carbon footprint of 280 kg CO_{2e}/m³ concrete according to an Environmental Product Declaration (EPD). The mix design modification reduced the cement by 11.4 kg/m³ and the fly ash by 2.0 kg/m³.

The impact of long term production using carbon dioxide was examined with a second producer who applied the concept to optimized mix designs for one year. The production data was compiled and examined. Data was collected on the total carbon dioxide injected and the number of doses delivered. A few assumptions were applied to this coarse data set could in order to estimate the overall production and cement savings.

Compressive strength was measured according to ASTM C39, unit weight was measure according to ASTM C138, slump was measured according to ASTM C143, and concrete time of set was measured according to ASTM C403.

4. Results and Discussion

Trial Run

The fresh properties of the two batches produced using the H30 mix design are shown in Table 1. The temperature was comparable for the two concrete batches. The slump was reduced in the batch containing CO₂ but a measurement of the unit weight confirmed that the batches had the same density. A measurement of the set time indicated that the carbon

dioxide addition did not impart any change. The fresh properties of both batches of concrete were deemed acceptable.

Table 1: Fresh properties of mix H30

Property	Control	0.1% CO ₂
Temperature (°C)	26.7	26.1
Slump (mm)	178	89
Unit weight (kg/m ³)	2470	2475
Set time	4h 25m	4h 27m

The compressive strength was measured at 3, 7 and 28 days and is summarized in Figure 3. In both cases the strength increased with time. The batch containing carbon dioxide was 25% stronger than the control at the earliest age, 14% stronger at 7 days and 12% stronger at 28 days – despite having 5% less binder.

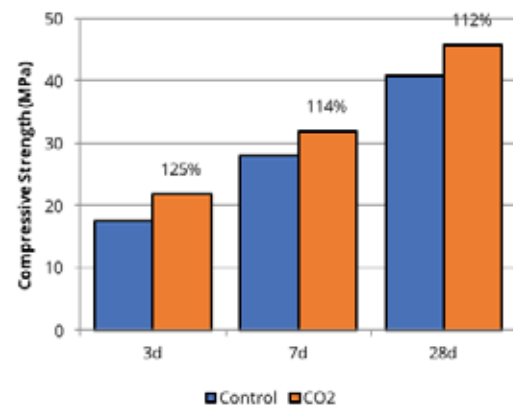


Fig 3: Compressive Strength of Mix H30

The compressive strength development was faster in the batch with the added carbon dioxide. The 3 day strength represented 62% of the 7 day strength and 43% of the 28 day strength in the reference concrete, whereas it was 68% and 48% in the concrete produced with CO₂.

The strength improvement suggests that, while additional data is needed to reinforce any conclusions, a greater cement reduction could be pursued. The compressive strength performance of the batch with carbon dioxide and a 5% binder reduction exceeded the typical performance.

The environmental benefit of the mix design change is dependent upon the carbon impact of the cement. A generic carbon intensity for cement production is 1.04 units of CO₂ per unit of cement. The mix design adjustment in this case would reduce the CO₂ footprint of the concrete by and estimated 3.1%.

The fresh properties of the batches produced using the 325P mix design are shown in Table 2. The temperature was shown to be slightly higher in the batch produced with the higher dose of CO₂. The slump of both CO₂ batches was lower than what was observed in the control. The carbon dioxide reduced the time to set by 28 minutes for the low dose and 18 minutes for the high dose.

Table 2: Fresh properties of mix 325P

Property	Control	0.08% CO ₂	0.35% CO ₂
Temperature (°C)	22.2	22.2	23.9
Slump	89	51	51
Set time	5h 0m	4h 32m	4h 42m

The compressive strength was measured at 2, 7 and 28 days and is summarized in Figure 4. The batch containing the low dose of carbon dioxide was 17% greater than the control at 2 days, 11% greater at 7 days and 99% of the reference at 28 days. The higher dose batch was very close to the reference strength being between 98 and 104% of the control across the three test ages. The improved/equivalent performance was achieved despite the CO₂ batches containing 5% less cementitious content.

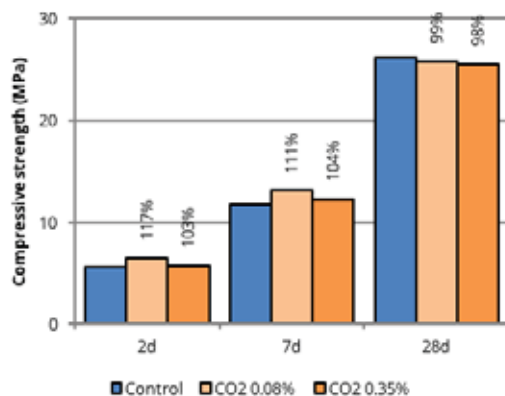


Fig 4: Compressive Strength of Mix 325P

The mix design adjustment in this case (a reduction of 11.4 kg cement/m³ concrete) would reduce the CO₂ footprint of the concrete by and estimated 4.2%

The environmental impact of the approach includes implementation emissions (associated with the process material and energy inputs), absorbed CO₂ (carbon dioxide converted into CaCO₃), and avoided CO₂ (carbon emissions associated with the cement that was not used).

The carbon dioxide is mineralized into carbonate reaction products at a rate estimated to be 60 to 90% (direct quantification of a low dose of CO₂ in concrete

is difficult due to the extreme precision required; a proxy test using a higher dose in masonry concrete suggested that the conversion efficiency would be 93% ±20% (at one standard deviation). A conservative calculation can assume a conversion of 70% of the dosed carbon dioxide. In the case of the generic case there would be 225 g CO₂ absorbed/m³ of concrete.

The implementation of the technology would result in some CO₂ emissions associated with capture and transportation of the CO₂ and the creation, transport and operation of the equipment. These emissions are sensitive to the electrical grid emissions where the capture takes place and the distance of transport but are on the order of about 13% of the CO₂ dosed [16]. A generic 27.6 MPa (4000 psi) mix design contains 338 kg cement/m³ concrete [18]. Therefore, a dose of 0.1% CO₂ by weight of cement required 321 g per cubic meter of concrete if the cement is reduced by 5%. The emissions to implement the technology totaled about 43 g of CO₂/m³ concrete.

Both the process emissions and the absorbed CO₂ is far exceeded by the avoided CO₂ emissions associated with the cement reduction. Generic specific emissions for cement are 1.04 tonnes CO₂/tonne finished cement). The 5% reduction of cement amounted to 17.6 kg CO₂ avoided/m³ concrete. The US National Average carbon footprint for a 4000 psi mix design is 393 kg CO_{2e}/m³ concrete [18]. A reduction in the carbon footprint by 17.6 kg CO₂/m³ concrete would represent a 4.5% decrease.

Operation Over One Year

A producer that used the technology for one year applied the technology to a range of mixes with an average 5% cement reduction. Production data was collected for one year and is summarized in Table 3.

Table 3: One year production summary at a facility using the CO₂ injection technology

Property	Monthly Average	Cumulative
Loads of Concrete	602	7,227
CO ₂ Injected (kg)	710	8,518
Cement avoided (tonnes)	-37	-448
CO ₂ Avoided (tonnes)	-39	-466
CO ₂ Converted (kg)	-497	-5,963
Emissions (kg)	95	1,144
Net CO ₂ Benefit (tonne)	-39.4	-473.3
Concrete produced (m ³)	3,684	44,204

The data recorded the total number of injections (loads of concrete) and the total amount of CO₂ delivered. The dosage rate (0.10% by weight of cement in calculations) was used to determine the

amount of cement in each batch of concrete and thus the avoided cement if the loading was 5% lower than the cement loading in an equivalent batch produced without CO₂.

The carbon impact of the avoided cement used the industry average cement emissions intensity [19] while the converted CO₂ was calculated as product of the overall injected CO₂ and the 70% conversion rate. The process emissions were determined as 13% of the dosed amount of carbon dioxide.

The net benefit was then the sum of the avoided CO₂, converted CO₂ and emitted CO₂. The overall benefit was estimated to be a net reduction by 10.7 kg CO₂/m³ concrete.

The scale of the net benefit was far greater than the amount of CO₂ utilized. It was clear that the small amount added (193 g CO₂ dosed/m³ concrete produced) was a platform on which a much larger environmental benefit could be achieved. The net benefit was about 56 times greater than the amount of CO₂ utilized.

Novel Carbon Dioxide Sourcing

Merchant carbon dioxide is typically the by-product of an industrial process. Figure 5 shows that 74% of merchant CO₂ is produced as the by-product of a chemical reaction or combustion while 26% comes from natural sources (i.e. wells) [20]. The utilization of any by-product carbon dioxide can be an environmentally positive step since the CO₂, prior to being captured for a merchant application, can be considered an industrial emission. The most common by-product sources are ethanol production, ammonia production, and hydrogen separation/refining. The smallest source is cogeneration other niche process (e.g. titanium pigment manufacture, breweries).

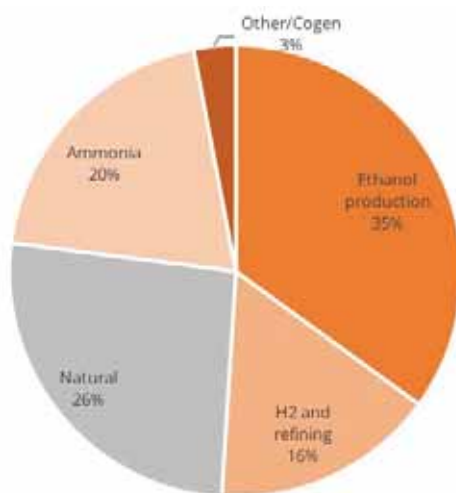


Fig 5: Source distribution of merchant carbon dioxide

While not yet a marketplace reality, the ideal source of carbon dioxide for a CO₂ utilization technology in

concrete production is from the emissions stream of a cement plant. Such an approach would link another waste stream with concrete production. If the industry's waste carbon dioxide could be repurposed to make better, cheaper and/or lower carbon concrete then the opportunity is not only enticing but synergistic.

The industry readiness for cement kiln carbon dioxide capture was examined in a 2016 study [21]. Five promising carbon capture technologies were compared but none of them are projected to be widely available for the next 10 to 25 years. Challenges include enormous capital and operating costs, the need to implement major changes to the cement process, large physical footprint of the capture technology, and lack of progress to a 50 tpd pilot level. Even an amine scrubbing-based carbon capture system, subject of much study with regards to integration into coal fired power generation, is not thought to be widely available until 2025. The capture technologies would aim to capture the majority, if not the entirety, of the carbon emissions from a cement plant. However, the landscape for CO₂ utilization can target "just enough" levels of carbon dioxide production that would be achieved at a much a smaller scale than full capture. A slipstream approach at a lower scale can avoid some of the complexities associated with full integration.

The potential output of cement plant CO₂ can be estimated from industry statistics. In 2016, the United States had 97 cement plants with an estimated total output of 75.2 million tonnes of cement [1]. The average cement plant had an output of 775,000 tonnes of cement and, according to a generic emissions rate of a 1.04 kg CO₂/tonne of finished cement, an emission of about 806,000 tonnes of CO₂. Importantly, for a utilization context, the plants are distributed across the country (Figure 6) and superficially located in the immediate vicinity of downstream concrete production. Conventional merchant carbon dioxide sources do not have any specific geographic relationship to concrete production let alone the cement plant-concrete producer supply chain.



Fig 6: Location of cement plants in the United States

There are an estimated 5,550 ready mixed concrete plants in the United States [22]. Therefore, each

cement plant serves about 57 concrete producers. If a generic ready mixed concrete producer would use a dose of 0.15% CO₂ by weight of cement on 50,000 m³ of concrete with an average of 300 kg cement/m³ concrete then it would utilize 22.5 tonnes of CO₂ in a year. A network of 25 ready mix customers around a cement plant would have a CO₂ demand on the order of 560 tonnes. This would need less than 0.1% of the plant's emissions. Whereas fully integrated capture technologies would measure their success by addressing a large fraction of a cement plant's emitted carbon dioxide the actual requirements for the utilization technologies could be served by a small capture system with a lower capital cost. The networked CO₂ demand would be serviceable by a 1 to 2 tonne per day capture technology. The carbon dioxide produced by a cement plant could be turned into a potential revenue stream (the price of merchant carbon dioxide is 4 to 7 times the price of cement).

5. Conclusions and outlook

Concrete is the world's most widely consumed construction material. Concrete producers have pursued sustainable concrete production in the past through the reuse of industrial by-products. Recent research directions have established both the reality and possibility of adding cement industry carbon dioxide emissions to the beneficially reused wastes in concrete.

The industrial trials demonstrated that the carbon dioxide injection could be used to maintain compressive strength performance in concrete mixes where the binder loading was reduced. The savings of cement have an environmental benefit given the inherent carbon footprint of the cement. The CO₂ addition can be integrated into an adjusted mix design wherein 5% cement is removed. The process has the potential to reduce the carbon footprint of the concrete by 3 to 4% yet the mix would remain available to further carbon footprint improvements by other means. A producer that used the technology for a year saved almost 450 tonnes of cement and realized a net environmental benefit that was 56 times larger than the amount of CO₂ utilized.

Sourcing CO₂ from cement plants is not yet practiced either for full scale capture or addressed a industrial gas market need. A CO₂ utilization approach in ready mix concrete would be best addressed by a small-scale slipstream capture technology can be employed to meet the appropriate scale of the needed carbon dioxide. Cement producers would then able to able to put their waste CO₂ to a beneficial downstream use thereby upcycling a portion of their primary waste product and making more sustainable concrete.

Acknowledgements

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Parametric study of wetting of urban materials and its impact on the thermal comfort in a street canyon

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Abstract:

Pedestrian thermal comfort is influenced by radiant temperatures and local parameters such as air temperature, relative humidity and wind speed. Thermal and moisture properties of urban materials can strongly influence thermal comfort. The present study investigates the evaporative-cooling potential of different materials and their impact on thermal comfort. The proposed approach couples computational fluid dynamics (CFD) simulations of wind flow with the heat and moisture transfer in porous urban materials while accounting for solar and thermal radiation exchanges. The model is applied on a street canyon, where the temporal and spatial variations of the cooling effect due to deposited rain are investigated. The results show significant differences in evaporative-cooling potential due to rain for different porous materials. Variations in materials and total wetting amount lead to cooling effects with different extent and duration.

Keywords:

Urban microclimate, Computational fluid dynamics (CFD), Porous media, Heat and moisture transport, Evaporative cooling

1. Introduction

Urbanization leads to increased radiation entrapment and heat absorption and decreased convective removal of heat. The resulting heat island effect is further compounded by climate change. Also known for long, urban heat island impacts on thermal comfort and energy use. Building materials that are commonly used in the built environment, e.g. concrete, asphalt, brick, play an important role in the absorption, transport and storage of heat and moisture within this built environment. Such materials can increase sensible heat storage and absorption of short-wave radiation and lead to a decrease in evapotranspiration in urban areas. In addition, moisture storage and distribution within the built environment influence the microclimatic conditions, as moisture is the key agent of evaporative cooling.

The present study uses a fully-integrated microclimate model that takes into account the interactions between the aforementioned physical phenomena. The model solves for the wind flow, the temperature and relative humidity in the air, and the temperature and moisture content in building materials (Fig 1). Direct and diffuse solar radiation as well as thermal radiation with diffuse reflections are taken into account. The model allows for detailed temporal and spatial analysis of the effects of different parameters on microclimate. Further, different contributions to cooling can be evaluated, such as shading, convective cooling, sensible heat transfer due to rain and evaporation.

The proposed approach is used in a case study composed of an isolated three-dimensional street

canyon. Specifically, the influence of materials with diverse moisture transport properties on evaporative cooling and thus on surface and air temperatures is investigated. The wetting and drying cycles in urban building materials are greatly influenced by their moisture permeability. Therefore, the drying period of different materials following a rain event is investigated and its impact on thermal comfort is estimated.

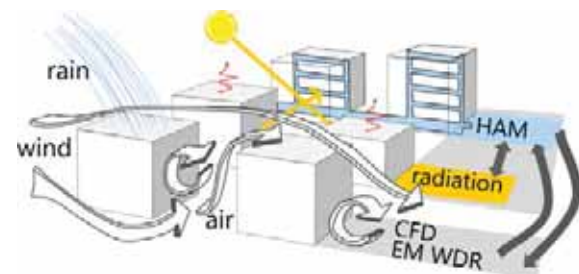


Fig 1: Schematic of the main physics implemented in the coupled urban microclimate model (EM WDR: Eulerian multiphase wind-driven rain, HAM: Heat and moisture transport)

2. Methodology

The wind flow is solved using 3D steady Reynolds-averaged Navier-Stokes (RANS) with the standard $k-\epsilon$ model [1]. In addition to RANS $k-\epsilon$ equations, governing equations for heat (as an active scalar) and moisture (as a passive scalar) transport are solved in the air domain. Buoyancy is modeled by taking into account the effect of temperature on air density based on ideal gas law. Heat and moisture transport in air and building materials are coupled in such a way that

the steady RANS equations are solved together with unsteady equations of heat and moisture transfer in building materials. This is repeated for each timestep on a typical day, namely the exchange timestep (10 min in this study). This approach is valid due to the fact that the time scale of transport in building materials is larger than the time scale of transport in air.

Absorption, transport and storage of heat and moisture are simulated within the building materials using coupled heat and moisture transport equations for porous media. In the present study, the continuum modeling approach is applied, where the different phases are not distinguished separately at a certain point in the material but, instead, the macroscopic behavior of the porous material is modelled. Within porous urban materials, the coupled heat and moisture transport equations are solved:

$$\left(c_0\rho_0 + c_l w\right)\frac{\partial T}{\partial t} + \left(c_l T \frac{\partial w}{\partial p_c}\right)\frac{\partial p_c}{\partial t} = -\nabla(q_c + q_a) \quad (8)$$

$$\frac{\partial w}{\partial p_c} \frac{\partial p_c}{\partial t} = -\nabla(g_l + g_v) \quad (9)$$

where w denotes moisture content, p_c capillary pressure, c_0 specific heat of dry material, ρ_0 density of dry material, c_l the specific heat of liquid water, T absolute temperature. The fluxes q_c and q_a denote conductive and advective heat transfer, whereas g_l and g_v denote liquid and vapor moisture transfer including latent heat. The moisture exchange at the exterior surfaces of building materials comprises the rain flux and the convective vapor exchange, whereas the heat exchange comprises the convective heat transfer, the radiative heat transfer, the sensible heat transfer due to rain and the latent and sensible heat transfer due to vapor exchange.

Solar (shortwave) and thermal (longwave) radiation heat transfer are modeled based on a radiosity approach. The direct component of incoming solar radiation is calculated with ray tracing. Multiple reflections of both solar and thermal radiation are calculated using view factors, which are calculated based on algebraic relations between surfaces. All surfaces are assumed to be opaque to both longwave and shortwave radiation. The model further assumes that surfaces are grey, i.e. emissivity and absorptivity are equal and independent of wavelength.

The numerical multi-transport model is implemented into OpenFOAM. For each exchange timestep, first, the steady air flow is solved. The heat and moisture fluxes at the coupled boundaries are used to solve transient heat and moisture transport in porous domains using adaptive timesteps [2]. For this, an internal iteration is performed, during which the

thermal radiative heat fluxes are updated until temperature and moisture content values converge. Finally, the new values for temperature and moisture at the solid boundaries are used to solve the steady air flow for the next exchange timestep. For a more detailed description of the model, the reader is referred to Kubilay et al. [3].

3. Case study

The case study is performed on an isolated three-dimensional street canyon, which is composed of two buildings with flat facades and horizontal roofs with a north-south orientation. Both buildings have the dimensions of height $\times$ length $\times$ width of $10 \times 10 \times 50 \text{ m}^3$. The computational domain is shown in Fig 2 as well as the orientation of the street canyon with respect to the wind direction and sun.

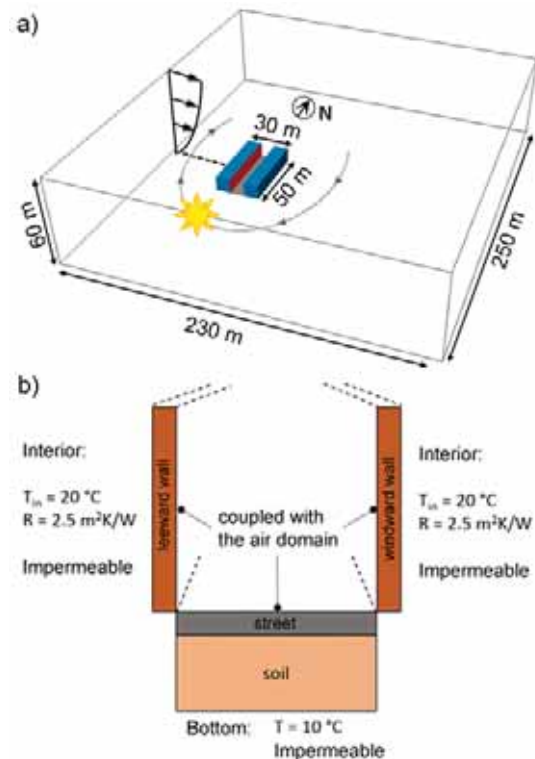


Fig 2: a) Computational domain and orientation of the street canyon with respect to wind direction and the sun. b) Configuration of the 3D models for the street-canyon facades and the ground (not to scale).

For simplicity, wind speed is assumed constant at 5 m/s at the building height. Wind direction is assumed perpendicular to the street canyon as shown in Fig 2(a), i.e. from west. The variation of ambient temperature and total solar radiation intensity are based on a typical early summer day with moderate ambient temperatures in Zurich, Switzerland [4].

Three-dimensional heat and moisture transport is considered within the porous materials in the street

canyon, i.e. the leeward facade, street and the windward facade. The coupled boundaries between the air and solid domains are represented in Fig 2(b). The leeward and windward walls of the street canyon are finished with an exterior layer of brick masonry with a thickness of 0.09 m. The outer layer of the street-canyon ground has a thickness of 0.10 m. Different materials are considered for the street: brick, soil and concrete. Beneath this layer, additional soil layer with a depth of 1.90 m is located for each case. Thermal properties for the dry materials are given in Table 1.

Table 1: Thermal properties of materials

Material	Density [kg/m ³]	Specific heat [J/kgK]	Thermal conductivity [W/mK]
Brick	1600	1000	0.68
Concrete	2280	800	1.50
Soil	1150	650	1.50

The study focuses on a duration of three days, where a rain event of uniform intensity is considered for 10 hours at nighttime between $t = 19.5$ – 29.5 h as shown in Fig 3. The distribution of surface wetting due to wind-driven rain is calculated based on an Eulerian multiphase model [5].

4. Results

Fig 3(a) evaluates the evaporative cooling resulting

from the different materials on the street surface by comparing the decrease in surface temperatures as a result of the wetting due to rain. In this case, the rain event has a uniform intensity of 1 mm/h. Once the rain event stops, the decrease in temperature starts to speed up for brick and soil. As solar radiation enhances evaporation, the decrease gets as large as 20°C for brick and 15°C for soil. The curves follow a similar trend for both brick and soil until about $t = 36$ h. Initially, the drying rate is high and at a similar rate for both materials as long as moisture transport within the material can sustain the evaporation rate. This is called the first phase of drying. However, soil cannot sustain this phase as long as brick due to its lower liquid permeability. At $t = 36$ h, soil enters the second phase of drying, where the surface relative humidity decreases and the surface temperature starts to increase. As a result, the drying rate decreases for soil due to the decreased moisture transport. Similar behavior is observed for brick much later at $t = 58$ h, where the decrease in temperature is limited to about 12°C. On the other hand, for concrete, surface temperature starts to increase as soon as the rain event stops. The reasons for this are the smaller amount of water absorbed in concrete and the lower liquid permeability of concrete, which result in a slower drying rate.

As the total wetting amount increases for soil in Fig. 3(b), it is observed that the materials stay in the first phase of drying for a longer duration. As the rainfall intensity increases, a higher amount of water is

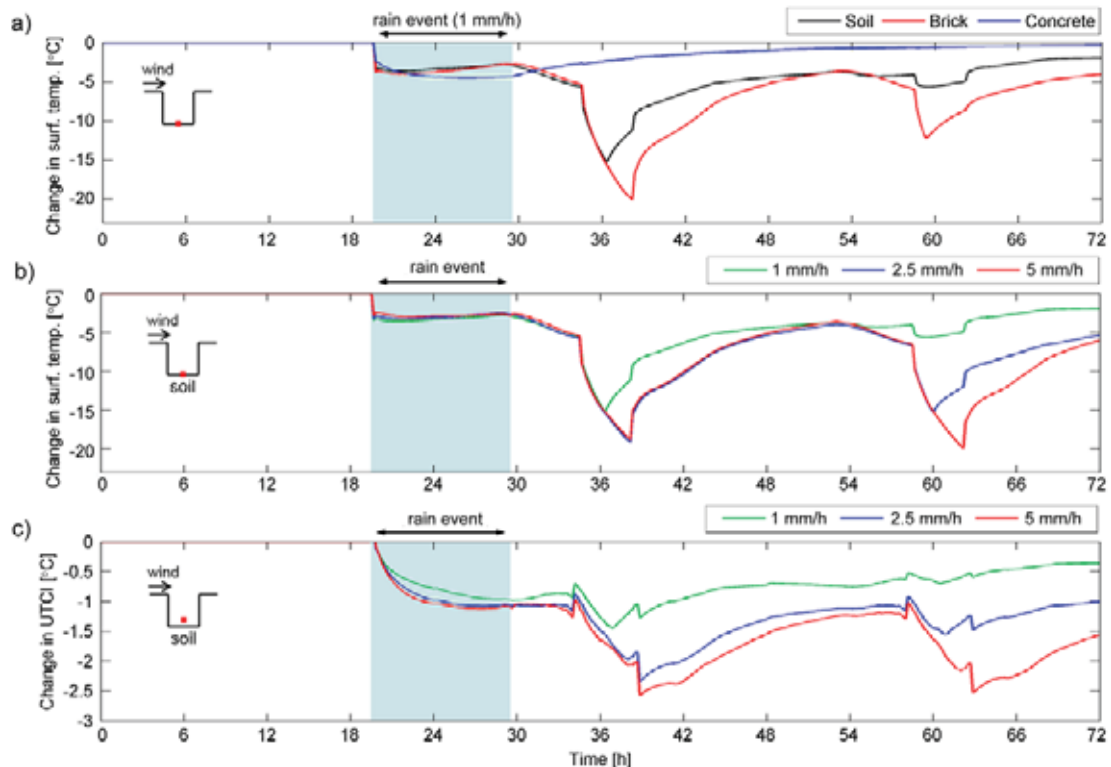


Fig 3: Temporal variation of change in street surface temperature a) for different materials at a rainfall intensity of 1 mm/h and b) at different rainfall intensities for soil on the street surface. c) Decrease in UTCI at different rainfall intensities for soil on the street surface.

absorbed and, hence, the material can maintain a high rate of evaporation for a longer duration. Note that, as the rainfall intensity increases, the maximum decrease in surface temperature remains constant at 20°C. This is also the same value observed in Fig 3(a) for brick. This is due to the fact that the evaporation rate depends on the environmental conditions during the first phase of drying. Therefore, external conditions such as radiation and convection dictate the maximum decrease in surface temperature.

Fig 3(c) evaluates the impact of evaporative cooling on pedestrian thermal comfort at a height of 2 m at the center of the street canyon. For this analysis, the Universal Thermal Climate Index (UTCI) [6] is used. The decrease in UTCI and the resulting improvement in thermal comfort follow a trend similar to what is seen in Fig 3(b) with increasing amount of wetting. A decrease of 1-2.5°C is observed depending on the rainfall intensity.

5. Conclusions and outlook

The influence of different urban materials exposed to environmental loading (wind, rain, solar radiation) on the surface temperatures in a street canyon is investigated. In order to achieve this, a fully-integrated 3D numerical urban microclimate model is used, which couples the heat and moisture transfer in porous urban materials with the local wind flow. The model provides detailed spatial and temporal distribution of heat and moisture, allowing the study of different contributions to cooling, e.g. convective cooling, sensible heat transfer due to rain, evaporation, as well as the comparison of heat storage and heat-removal and thermal comfort for different conditions.

The results show a significant difference in terms of evaporative-cooling potential due to rain for different porous materials on the street surface. Variations in materials lead to different durations of evaporative cooling. At higher rainfall intensities, the decrease in surface temperature remains the same as long as the porous material can transport enough moisture towards surface. On the other hand, the duration of evaporative cooling increases with increasing rainfall intensity. The largest improvement in the thermal comfort is achieved with materials with larger moisture permeability.

While this study focuses on the wetting of surfaces due to rain, a similar analysis can also be performed to assess active cooling strategies using stored water. Then, the model can provide valuable information on parameters such as the timing of wetting. Further work is planned on including the impact of evapotranspiration e.g. grass, green roofs and on evaluating the local effects of short-term phenomena, e.g. heat waves, at neighborhood scale.

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Monitoring the In-situ Freeze-Thaw Performance and Leaching of K-based Geopolymer Concrete Pavers

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Abstract

Geopolymer concrete (GPC) is a sustainable, eco-friendly construction material and a new innovative alternative to Portland cement concrete (PCC). Use of geopolymer reduces the demand of cement which is responsible for high CO₂ emission. Since the use of bottom ash and potassium-based in construction of geopolymer concrete is relatively limited, dealing with these industrial materials are now posing to be one of the most significant challenge in recent years. The effects of the freeze-thaw cycles recognized as the major contributors to the deterioration of structures including road pavements constructed in the cold regions, alongside, this sustainable material has so far not been implemented in major projects especially for pavements. Hence, as a mock implementation project, the parking lot, at University of Victoria, is assigned for placement of GPC pavers to monitor their performance when exposed to real environmental condition. This mock placement will allow monitoring the effect of freeze-thaw cycles and the effect of GPC on infiltrated water by monitoring leaching from pavers.

Keywords:

Geopolymer Concrete, Bottom ash, Potassium-based, Freeze-thaw Cycles, Leaching

1. Introduction:

The concept of a hygienic environment and low greenhouse gas emissions is a common concern especially in the construction industry. The produced carbon dioxide (CO₂) emissions are huge in producing only a ton of Portland cement, which is one of the main ingredient of concrete. So, to reduce greenhouse gas emissions, efforts are required to develop environmentally friendly construction materials. Geopolymer concrete (GPC) is an excellent alternative construction material to the existing plain cement concrete. Joseph Davidovits [1] proposed a theory that an alkaline liquid could be used to react with by-product material such as fly ash (FA) and rice husk ash to produce binders. Any material that contains Silicon (Si) and Aluminium (Al) is a possible source material for the manufacture of GPC. The existence of alkali activators in the mix design of GPC has a major effect on the properties of geopolymer. Alkaline liquid plays an important role in the polymerization process. The most common alkaline liquid used in GPC is a combination of sodium hydroxide (NaOH) and sodium silicate (Na₂SiO₃) but in this project, the potassium hydroxide (KOH) and potassium silicate (K₂SiO₃) were used to produce the GPC made by bottom ash (BA). Bottom ash is the coarse ash fraction produced by coal-fired power station when pulverised fuel is burned at high temperature and pressure and it has similar chemical properties to fly ash, consisting of silica and alumina. Since the use of bottom ash in construction of GPC is relatively limited, dealing with this industrial material is now posing to be one of the most significant challenge in recent years.

Cracks and spalls can be introduced to the concrete structures during their life cycle due to the progressive expansion and contraction in cold environments. Deterioration proceeds as freeze-thaw cycles are repeated, and the concrete structure progressively loses its strength. Therefore, frost damage is a fatigue process and it has been a practical issue to improve the freeze-thaw durability and to prolong the service life of concrete. Hence, another challenge that can be highlighted in GPC studies is freeze-thaw resistance of concrete in sub-zero temperature areas [2].

Leach-ability of concrete is another important concern and interest topic in engineering, which should be considered in environmental studies. Leaching is the process by which a liquid dissolves and removes the soluble components of the concrete to the environment. Several past studies [3] have evaluated possible issues posed by elevated PH and heavy metals in Portland cement concrete (PCC) leachate, though only minimal information is available for K-base GPC made by bottom ash. Additionally, more realistic experimental simulation should be performed to evaluate the interaction of GPC leachate with drinking water.

2. Literature review

P. Sun and H.-C Wu [4] investigated the freeze-thaw resistance of fly ash-based alkali activated mortars at ambient conditions. In this study, specimens of various compositions were exposed to standard freeze-thaw cycles. Samples were then kept into a freezing-thawing

tray made in-house. The tray was filled with distilled water and covered with a plastic film to avoid water loss during the test per ASTM C666 [5]. The result showed that fly ash based specimens showed no deterioration up to 24 weeks. All the fly ash specimens showed continuous increases in mass, dynamic modulus, and compressive strength with time.

Yawei Fu et al. [6] studied the effect of freeze-thaw cycles on Na-based alkali activated concrete. In this regards, 6 specimens were casted to test the properties of concretes and the average of results served as the freeze-thaw resistance. The results exhibited that slag based alkali activator concrete had lowest damage with frost-resisting grade of F300 and also had lowest mass loss. So concrete can efficiently restrain freeze-thaw damage of concrete from worsening.

Vlastimil Bilek et. al. [7] investigated the mechanical properties and durability of alkali-activated concrete (AAC). In this study, non-destructive tests were performed to measure the compressive strength. Prism were exposed to 125 freezing and thawing cycles. One cycle represents 4 h in the freezer in temperature $-20\text{ }^{\circ}\text{C}$ and 2 h in water $+20\text{ }^{\circ}\text{C}$. After the cycles, the properties of concrete were measured. Based on the results, the strengths increase with water/slag ratio reduction. Frost resistance depends strongly on the design of AAC and even though the compressive strength of concrete is high, the frost resistance of AAC can be very bad.

2.1 Air Entraining Agent

S.kvara et al. [8] investigated the resistance of fly-ash-based geopolymer mortar specimens to alternating freezing and defrosting cycles, according to Czech Standard CSN 72 2452. The specimens were cured under laboratory conditions at ambient temperature and 40% relative humidity (RH) for 28 days before freeze-thaw testing. Seven mixture designs were made, adding various materials, such as OPC, limestone (in ground or aggregate form), and three different air entraining agents. Samples were broken after 28 days, 6 months, and 1 year, respectively. The compressive strength values of samples decreased slightly after the defrosting cycles, compared to the values for the samples without exposure to frost tests. Still, no physical deterioration by means of damages or deformations was noticed, indicating that fly-ash-based geopolymers were considerably resistant to frost exposure. Similar conclusions have been reported for fly ash mortars, in comparison to OPC-based specimens.

T. Bakharev et al. [9] investigated the effect of admixture on properties of alkali-activated slag (AAS) concrete including air entrained admixture (AEA). Then the effect of admixtures on workability, compressive strength, and shrinkage was investigated mainly for concrete with sodium silicate activator. OPC concrete samples were used for comparison. AEA were the most effective admixtures for improving workability. Air-entraining was effective in reducing shrinkage in alkali activated slag concrete; AEA also greatly improved workability. Thus, it

was considered that AEA is the most suitable for use in alkali activated slag concrete.

2.2 Leaching

Arioz et al. [10] activated an F-type fly ash with 12M NaOH solution and water glass in their research. The specimens were cured at 40, 80 and $120\text{ }^{\circ}\text{C}$ for 6, 15 and 24 hours residence time. The broken specimen at 28 days was tested by leaching using ICP-OES for the leached element analysis. According to the US EPA 1311 method [11] the pH of the acetic acid used as a solvent was set to 4.93 ± 0.05 before the leaching test. The ratio of liquid-to-solid material was 20:1. After 18 hours contact time the slurry was filtered and the liquid phase was measured by ICP-OES. It was concluded, that the As and Hg could be immobilized in the structure, while the other examined metal ions (Zn, Cr, Pb and Cd) were not.

Izquierdo et al. [12] compared the solubility of elements in geopolymer and in raw fly ash. They found that the fly ash based geopolymer is suitable for the immobilization of many trace elements, such as Be, Bi, Cd, Co, Cr, Cu, Nb, Ni, Pb, Sn, Th, U, Y, Zr and the rare earth elements. However, the leached amount of some elements was higher in geopolymers in aqueous solution as compared with raw fly ash. As the effect of strong alkaline condition after geopolymerization caused by the unreacted alkali content, the elements due to their mobility can form As, B, Mo, Se, V, W oxyanions. Their concentration was found to be increased. This means that the ash composition, an optimal composition of the activator solution, the ratio of activator solution and the circumstances of production are very important in order to achieve a stable final product exhibiting a low mobility of the elements.

Zhang et al. [13] investigated the immobilization of Cr^{6+} , Cd^{2+} , and Pb^{2+} for geopolymer concrete. Static leaching tests were carried out on all samples under ambient temperature ($\sim 25 \pm 5\text{ }^{\circ}\text{C}$), in sealed plastic containers in order to prevent continued absorption of oxygen and carbon dioxide from the atmosphere. Based on the results, Pb is immobilized very efficiently, Cr (VI) immobilization is quite ineffectual and Cd is not very effective at low PH.

3. Experimental Procedure

3.1. Fly ash and Bottom ash

Based on ASTM C618 [14], three classes of fly ash (class N, F, C) are desired for use in GPC mix design but among those, class F were selected as it is a pozzolanic material and useful for developing the mix design. The chemical composition are showed in Table 1.

Table 1 Chemical Compositions of fly ash and bottom ash

Properties	Fly ash (%)	Bottom ash (%)
SiO ₂	47.1	60.11
Al ₂ O ₃	17.4	14.35
Fe ₂ O ₃	5.7	5.92
CaO	14	10.40
MgO	5.4	4.49
SO ₃	0.8	0.10
LOI	0.19	0.00
Na ₂ O	N/A	2.232
K ₂ O	N/A	1.766
TiO ₂	N/A	0.892
P ₂ O ₅	N/A	0.200
Mn ₂ O ₃	N/A	0.093

The bottom ash used in this investigation comes from the pulverised coal combustion in Lafarge Power Plant (Vancouver, Canada). The chemical composition has been determined by XRD for measuring elements in combustion residues from coal utilisation properties. The major components in bottom ash are silicon oxide, aluminium oxide and iron oxide. Trace amounts of MgO, CaO, Na₂O and K₂O are also detected. The specific gravity of the bottom ash is low, due to the porosity of the particles. The chemical composition, loss of ignition (LOI) and specific gravity of the bottom ash are showed in Table 1.

3.2 Alkali liquid

In this study, a combination of potassium silicate solution and potassium hydroxide solution was chosen as the alkaline liquid. Potassium hydroxide solutions were chosen with technical grade in flakes form and obtained from Sigma-Aldrich Pty Ltd, Canada. The potassium hydroxide (KOH) solution was prepared by dissolving the flakes in water. The mass of KOH solids in a solution varied depending on the concentration of the solution expressed in terms of molar, M. Potassium silicate powder (AgSil 16) obtained from PQ Cooperation (USA) was used and based on the MSDS file of company, chemical composition of the K₂SiO₃ Powder was K₂O = 32.4%, SiO₂ = 52.8% and water 14.8% by mass.

4. Construction Details

The site is located at the parking lot 3 of University of Victoria. The placement size is 89 ft² and covers the entrance of parking lot. 200 GPC paver blocks were casted in material laboratory of University of Victoria

and 200 PCC paver blocks were purchased from HOME Depot Retailer in Canada. The installation of paver blocks were performed in three stages: excavation, subbase fill, and the paver block placement. Figure 1 shows the cross section of the construction.

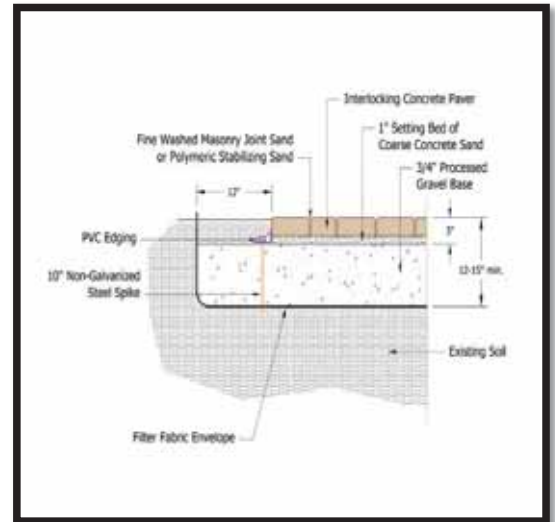


Figure1. Cross Section of paver block execution

Table 3. Shows the used materials for installation of paver blocks.

Table2- Materials

Gravel Base ¾"	192000 in ³
PVC Edging 6' x 7	6' x 7 20 kg
Joint sand polymeric sand	
Jumping Jack Vibratory plate compactor	250 rpm
Bedding Sand	25600 in ² c33 concrete Thickness= 25mm
Materials	Quantity
Gravel Base ¾"	192000 in ³
PVC Edging 6' x 7	6' x 7 20 kg
Joint sand polymeric sand	
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Bedding Sand	25600 in ² c33 concrete Thickness= 25mm

Table3-Area Dimensions	
Paver Block Dimension	8 in.×2-1/4 in. ×4 in
Area of Paver block	32 in ²
Area 1	NO. 50
Area 2	NO. 350
Area 1	1600 in ²
Area 2	11200 in ²



Figure2. Assigned area



Figure3. Top view of site

5. Execution of paver blocks

The paver blocks placement were divide into two area as the accessibility of traffic to the parking lot was compulsory. Area 1 was assigned to collection of water for leaching test and area 2 was assigned for investigation of properties of both GPC and PPC under real environmental conditions.



Figure4. Excavation



Figure5. Soil Compaction



Figure6. Gravel Placement



Figure7. Gravel Compaction



Figure 10. Final Compaction



Figure8. Bedding Soil Placement



Figure11. Final Placement

6. On-going Research

Non-destructive testing (NDT) is defined as the course of inspecting, testing, or evaluating materials, components or assemblies without destroying the serviceability of the part or system. NDT will be used to investigate the effect of freeze-thaw cycles on the mechanical properties of PCC and GPC pavers for cycles of months in real environmental conditions.

6.1. Compressive strength

In this project, Schmidt hammer will be used to determine the compressive strength of paver blocks in the site and compressive strength of extra paver blocks will be tested by using the compression testing machine in University of Victoria laboratory. Randomly, 20 numbers of GPC and PCC paver blocks will be selected to find the average of compressive strength of blocks after some cycles of freeze-thaw happen in-situ.

6.2. Resonant Frequency Test

Resonant Frequency Test is another NDT to determine the modulus of elasticity of GPC and PCC.

In this research, efforts will be made to predict the compressive strength of paver blocks by following ASTM C215 [15], named as Resonant Frequency Test (RFT) and the dynamic elasticity will be measured from resonant frequency test.



Figure9. Paver block placement

6.4. Leachate Test

Geopolymer matrices give rise to a leaching scenario characterised by a highly alkaline environment, which inhibits the leaching of heavy metals but may enhance the mobilization of certain oxyanionic species.

In this regard, paver block were kept in curing tank and water was collected at age of one day. PH, total alkalinity, copper, total hardness, phosphate, total iron, nitrate and nitrite were measured by using strips. Table 4. Shows the preliminary results of leachate test.

Table 4. Leachate

pH	9
Total Alkalinity	Over 240
Copper	0.2-0.5 mg/L
Total Hardness	1.5
Phosphate	5-15 ppm
Total Iron	0.15 mg/L
Nitrate	1-2ppm
Nitrite	0.15-0.3 ppm

7. Conclusion Remark

- This project is defined to investigate the mechanical properties of GPC and PPC in parking lot of University of Victoria.
- Perforate pipes are embedded under the paver block to monitor the leachability of GPC in real environmental conditions.
- The compressive strength, modulus of elasticity and leaching of heavy metal will be measured each 3 month as some cycles of freeze-thaw happen in-situ.

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Energy harvesting using smart sensors for civil applications

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Abstract:

Civil structures like bridges, satellite launch pads etc. experience a spectrum of vibrational load frequencies during its operational life time. These conditions make it inevitable to monitor the health of these structures on line, which calls for deployment of a number of sensors across the structure. The powering of these sensors can be made autonomous, if we can convert the existing vibrational energy into electrical energy. This paper provides a review of the various approaches that are being investigated by researchers for energy harvesting from vibrations and identifies the challenges associated with it. The material, Lead Zirconate Titanate (PZT) $\text{Pb}[\text{Zr}_x\text{Ti}_{1-x}]\text{O}_3$ has a large piezoelectric coefficient and various designs of PZT based harvesters have been studied, such as bulk type or cantilever type. The cantilever type harvesters work effectively in the case of vertical vibrations. However, they can also be designed to capture the energy present in other directions, applying methods like adding moving mass into the system. Various designs of MEMS (Micro Electro Mechanical Systems) based energy harvesters have been tried out, to power the low current MEMS sensors. Since a PZT based harvester has high efficiency at its resonance frequency, matching the natural frequency of the harvester with the ambient vibration frequency, is the key element in the design. This paper also gives a brief about lead free piezo electric materials, such as Barium Titanate, which are being studied extensively now.

Keywords:

Structural health monitoring, energy harvesting, vibrations, piezoelectric

1. Introduction

Piezoelectric materials have the property of generating voltage when subjected to mechanical stress, which is the direct piezoelectric effect. When a voltage is applied across a piezo electric material, it undergoes a mechanical deformation. This effect is referred to as converse piezoelectric effect. In piezoelectric materials, the centers of positive and negative charges do not overlap, generating dipole moments. Piezoelectric effect is the electromechanical interaction, which is linear. Electric charges get collected in these materials, on application of stress. . The positive and negative electric charges are separated, but they are normally symmetrically distributed, making the material electrically neutral. Each of these sites makes an electric dipole and dipoles near each other try to get aligned in regions, which is called Weiss domains. These domains are randomly oriented, but can be aligned by poling. During poling, the material is subjected to a very high electric field that orients all the dipoles in the direction of the field. When a mechanical stress is applied, this symmetry is disturbed and the charge asymmetry leads to a voltage across the material.

The electromechanical coupling depends on the piezoelectric properties, the size and shape, frequency and the direction of mechanical excitation and electrical response.

Electromechanical coupling factor is the indicator of the effectiveness by which a piezoelectric material converts mechanical energy into electrical energy and vice versa. Here, we look into the various approaches adopted by researchers to harvest electrical energy from mechanical vibrations, using piezoelectric materials.

2. The electrical behavior of the piezoelectric material

The electrical behavior of the piezoelectric material is given by

$$D = \epsilon E \quad \dots\dots\dots(1)$$

Where D is the electric displacement, ϵ is permittivity and E is electric field strength,

The mechanical behavior of the material is given by Hooke's law,

$$S = St \quad \dots\dots\dots(2)$$

Where S is strain, s is compliance and T is stress. These can be combined to get the coupled equations,

$$\{S\} = [s^E] \{T\} + [d_t] \{E\} \dots\dots\dots(3)$$

$$\{D\} = [d] \{T\} + [\epsilon^T] \{E\} \dots\dots\dots(4)$$

where d represents the piezoelectric constants, and the superscript E indicates a zero, or constant, electric field; the superscript T indicates a zero, or constant, stress field; and the subscript t stands for transposition of a matrix.

Ceramics such as PZT have high stiffness and high electromechanical coupling coefficient. They are classified based on the coupling between the direction of poling and the direction of maximum deformation.

There are two modes for the piezoelectric materials - 33 mode and 31 mode.

In the case of 33 mode, the charge will be collected on the surface, perpendicular to the polarization axis and the mechanical force is along the polarization axis. In the case of a 31 mode of piezoelectric material, charge is collected on the surface, perpendicular to the polarization axis and the mechanical force is perpendicular to the polarization axis. Selection of the mode can be made based on the loads coming on the piezoelectric material

3. Vibration energy harvesting

Energy harvesting from low frequency applications using piezoelectric materials had been a challenge. In an effort to eliminate the replacement of the batteries of electronic devices that are difficult or impractical to service once deployed, harvesting energy from mechanical vibrations or impacts using piezoelectric materials has been researched over the last several decades. However, a majority of these applications have very low input frequencies. This presents a challenge for the researchers to optimize the energy output of piezoelectric energy harvesters, due to the relatively high elastic moduli of piezoelectric materials used to date. Harvesting devices for low frequency (0–100 Hz) applications have been developed by various scientists [1] and \ methods have been developed to improve the power outputs of the piezoelectric energy harvesters. Various key aspects that contribute to the overall performance of a piezoelectric energy harvester are geometries of the piezoelectric element, types of piezoelectric material used, techniques employed to match the resonance frequency of the piezoelectric element to input frequency of the host structure, and electronic circuits specifically designed for energy harvesters. Generally, a cantilever beam with piezo electric material attached to it (figure1) is used for

energy harvesting. Typical dimensions of the cantilever beam can be 15cmx4cm, which is suitable for a bench test. Piezoelectric material can be a stack or a patch, surface bonded to the beam.

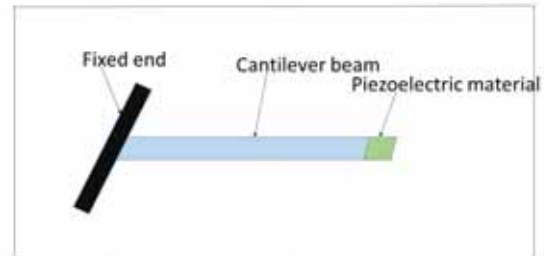


Figure 1 Cantilever beam with piezoelectric element

A typical setup for vibration energy harvesting using piezoelectric material is given in figure 2.

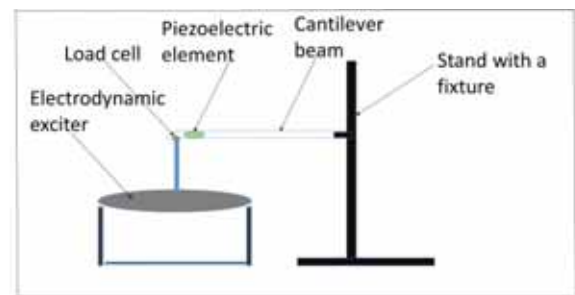


Figure 2 Setup for vibration energy harvesting

The electro dynamic exciter is used for generating vibrations of various frequencies and amplitudes. The exciter is driven by a function generator and a power amplifier. The cantilever beam is of dimensions 15cmx4cm.

A typical rectifier circuit along with a storage unit is given in figure 3.

The circuit has to be designed with appropriate values of rectifier diodes and the capacitor. This is critical because, the input impedance of the circuit has to be matched with the output impedance of the harvester, in order to minimize the energy loss. Energy storage device can be capacitors, super capacitors or lithium batteries.

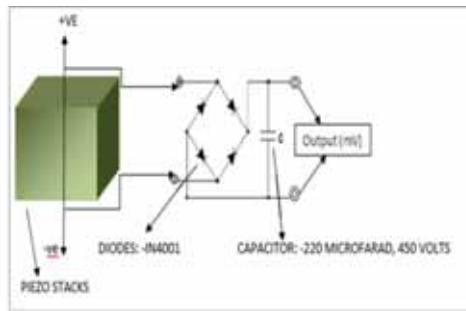


Figure 3. A typical circuit for energy harvesting

Piezoelectric elements can be designed as stacks or patches., depending on the application. Macro Fiber Composites (MFC) are patches fabricated from piezoelectric fibers.(ref. Smart Material Corporation). The structure of MFC is given in figure 4

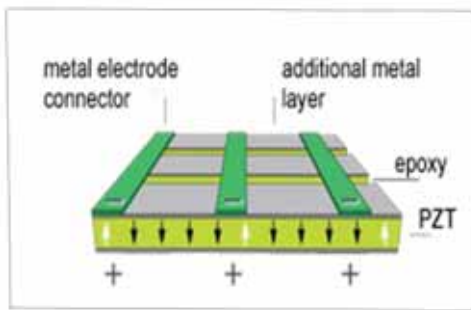


Figure 4. Structure of MFC(Ref. Smart Material Corporation)

Macro Fiber Composites are designed with piezoelectric fibers of square cross section and bonded with an epoxy. The interdigitated electrodes get maximum area of contact, due to the square cross section. This leads to a better output.

Recent advances in ultralow power portable electronic devices and wireless sensor network, require limitless battery life for better performance. Piezoelectric materials have high energy conversion ability from mechanical vibration [2]. Piezo electric polymers also can be used to harvest energy [3], specifically from activities like walking and similar body movements. These materials can be incorporated in a shoe and the charge can be stored. Poly vinylidene fluoride is used as the converting element.

The California Energy Commission [4] works towards better understanding of piezoelectric material based energy harvesting technology in roadway and railway

applications. This attempt was to assess the results of piezoelectric energy harvesting technology has the potential to match the required performance, reliability, and costs of existing renewable technology. This is a great step towards planning a practical application for this technology in transport infrastructure. Similarly bike vibrations also can be harvested using piezoelectric generators in order to power portable devices. [5]. Structural Health Monitoring [SHM] is a field of growing interest with a wide range of applicability, like civil structure, aerospace systems and automobile structures. In order to have SHM in place, it is necessary that, a large number of sensors be deployed across the structure and powering them usually comes out to be a big challenge as wiring will not be feasible in most cases and once decides for battery, recharging them becomes a limiting factor. Once the power requirement is calculated, [6] appropriate energy harvesting and storage approaches can be incorporated. Charging time and the extent to which charging can be done are parameters that are studied [7] for Macro Fiber Composites, Lead-Zirconate-Titanate, the bimorph actuator, using a nickel metal hydride battery. Many researchers have arrived at prototypes of vibration energy harvester designs, suitable for different applications. [8]. Many attempts have been made to model, design and optimize a piezoelectric generator based on a two layer bending element [9]. It is reported that designs of 1 cm^3 in size generated using the model have given a power output of $375 \mu\text{W}$ from a vibration source of 2.5 m s^{-2} at 120 Hz and a 1 cm^3 generator could be used to power a custom designed 1.9 GHz radio transmitter from the same vibration source. A low frequency vibration energy harvester has been designed [10] with a PZT cantilever, incorporating a micromachined silicon proof mass on it. The effective volume of the fabricated device is about 0.7690 mm^3 . The average power density obtained is $416 \mu\text{W}/\text{cm}^3$.

It is reported [11] that with lead zirconate titanate multilayer piezoelectric stack (PZT-Stack), energy was transferred from the stack to a super capacitor. The power delivered to a matched resistive load was also studied. It is demonstrated that 35 percent mechanical to electrical energy conversion efficiency is possible. The capacitance and piezoelectric coefficient of the PZT-Stack were dependent on the dynamic stress. A numerical study on the output power and the energy conversion of piezoelectric rectangular and hexagonal nano wires and nanofins [12] is carried out, which is important during a design. A scheme is proposed [13] to split the electrode of a monolithic piezoelectric vibration energy harvester to many equal regions and to connect them in series. The advantage of this scheme is that it provides a wide operating voltage range and a higher output power. One of the common approaches to increase the frequency bandwidth of a harvester is to design nonlinear harvesters. A new design [14] consists of a cantilever beam with a tip mass mounted vertically and excited in the transverse direction at its base.

This design introduces two wells for large tip masses, when the beam gets buckled. However, it is restricted by a few frequencies, which can be covered by the design of the wells and locations. Another approach to increase the bandwidth is to go for a design, incorporating two stage device [15]. Other methods being tried out are, multi stacking and stretching [16] of ferroelectric films on cantilevers. The output power of stretched-film harvesters was found to be 3.6 times the output of the un stretched films. Microfabricated piezoelectric vibration harvesters have been under study and an experimental verification of the proposed models have been carried out [17].

The distribution of piezo electric material can be optimized using porous material [18] to improve the

harvested energy output. The effect of porosity on the power generated is demonstrated through modeling and by experiments. Ocean waves are a potential source of electrical energy [19] and piezoelectric materials can be effectively used to tap this energy. The interaction between aerodynamics, structural vibration and electrical response of the piezoelectric generator has been modelled. The power conditioning circuit design can influence the power that can be drawn from the piezoelectric harvester [20]. A piezoelectric power conversion based on a nonlinear voltage processing is implemented and could achieve 4 times the original output. It is demonstrated [21] that by compensating the voltage after each inversion at the output of the harvester, the harvested power can be increased by 14% in the case of parallel inversion and over 50% in the series inversion, compared to the case when no compensation is used. The distribution of piezoelectric material can be optimized using porous material [18] to improve the harvested energy output. The effect of porosity on the power generated is demonstrated through modeling and by experiments. Ocean waves are a potential source of electrical energy [19] and piezoelectric materials can be effectively used to tap this energy. The interaction between aerodynamics, structural vibration and electrical response of the piezoelectric generator has been modelled. The power conditioning circuit design can influence the power that can be drawn from the piezoelectric harvester [20]. A piezoelectric power conversion based on a nonlinear voltage processing is implemented and could achieve 4 times the original output. It is demonstrated [21] that by compensating the voltage after each inversion at the output of the harvester, the harvested power can be increased by 14% in the case of parallel inversion and over 50% in the series inversion, compared to the case when no compensation is used.

One of the common sources of vibration energy is the tires of a vehicle. Piezoelectric energy harvester is designed to adapt to the tire vibration spectra and the super imposed acceleration signal [22]. An artificial neural network (ANN) based closed loop system is put forward to take care of broad band operation. The harvester is used to power the sensor

net work in the tire. The tire sensor data is transmitted using this power too. Mathematical modeling of the cantilevered beams with PZT layers is worked out [23], applying damping models to generate more realistic conditions.

a. Lead free piezoelectric energy harvesters

As we have seen so far, PZT is an efficient vibration energy harvester even though frequency tuning is a challenge to be resolved. However, in recent period, there is a growing concern over the environmental hazard that PZT can generate due to the toxicity of the material. This awareness has triggered an involving research in search of lead free materials, which can function as an effective energy harvester.

In one such attempt, piezoelectric MEMS energy harvesters (EHs) of lead-free $(K,Na)NbO_3$ (KNN) thin films have been microfabricated on stainless steel cantilevers [24] rf-magnetron sputtering is made use of to directly deposit KNN films onto Pt-coated stainless steel cantilevers. KNN thin-film EH of length: 7.5 mm, width: 5.0 mm, weight of tip mass: 25 mg, gave a large average output power of 1.6 μW , when subjected to vibration at 393 Hz and 10 m/s^2 . Experiments conducted using Mn-doped $BaTiO_3$ -based ceramics produced greater power [25]. The harvester is designed as a unimorph.

Experiments are also carried out using AlN as piezoelectric material [26]. The micromachined harvesters are designed for different geometries and for resonant frequency range of 200 hz to 1200 hz. The power output reported is comparable with that of PZT. Research is also on developing lead-free piezoelectric materials [27] based on solid solution having composition $(KNa)NbO_3-xABO_3$, (where A = Li, and B = Nb; $x = 0, 5, 5.5, 6$, and 6.5 wt%). The best results are obtained for the composition $K_{0.5}Na_{0.5}NbO_3 - 6.5\%LiNbO_3$.

Mn-doped $BaTiO_3$ -based ceramics [28] seems to have produced greater power and energy compared to conventional PZT harvesters.

Piezoelectret foam is a lead-free, polymer-based electret material exhibiting piezoelectric-like properties [29]. Research has been carried out on the fabrication and operation of this material for power generation. A theoretical model is developed and compared with the experimental results. The foam is used to charge a capacitor, which gotcharged to 4.67 v in 30 minutes.

A thin film MEMS vibration energy harvester has been designed and fabricated [30] using Aluminium Nitride as piezoelectric material. Vacuum packaging is given to maximize the output power. The harvested power is used to power a sensor network, which required less than 10 μW .

4, Challenges associated with Piezoelectric material based energy conversion

a. Frequency dependence

Usually the harvester is designed as a cantilever beam, since this produces the highest average strain for a given input force. A typical harvester consists of two lead zirconate titanate layers bonded on two sides of a steel shim and a proof mass at the tip. Ambient vibrations are transferred to the unit through the base of the cantilever. Bending strains during the oscillations are converted to an AC voltage by the material. For enabling high efficiency, the frequency of the vibrations has to be matched with the resonant frequency of the harvester. Most ambient vibrations are at low frequencies. The widely used method to reduce the natural frequency of the harvester, is to add proof masses, which will actually make the unit bulky. However, the proof mass leads to an increased mechanical energy stored in the cantilever-mass system, thereby improving the harvesting efficiency.

b. Current associated with the voltage very low

The research in the field of energy harvesting mainly focusses on how to improve the power associated with the harvested energy, as the harvested electric charges are associated with low currents. This becomes a concern in the case of applications where actuation is involved.

c. Coupling coefficient is low

Overall electromechanical coupling coefficient has to be improved to yield higher conversion efficiency. This has to be achieved by material tailoring and harvester design modifications.

5. Application in MEMS (Micro Electro Mechanical Systems)

As research is being carried out towards improving the system as per the above mentioned issues, focus is also towards using the current technology- MEMS. The latest CMOS technologies to enable fabrication of very small sensors and other electro mechanical elements in a MEMS device with very low power requirement. The challenge in this technology is that its size and cost are limited by the batteries that are used. Replacement of batteries in these devices is not feasible. Hence, if we can generate power autonomously for these MEMS units by energy harvesting, it is going to resolve the major technical issue associated with MEMS. It can also bring out a self supporting system without the need for a battery. The method being tried out is, to maximize the available power per unit volume, as the size becomes critical in MEMS. Another point to be noted is that the electro mechanical coupling coefficient of thin film is less than the bulk ceramics. Hence literature talks about bonding bulk ceramic on the Si substrate and thinning it to achieve the desired dimensions. MEMS based health monitoring of bridges can be enabled by a power source based on vibration energy, which is already available on the bridge.

6. Discussions

The materials used for structural design are no more the conventional materials. The research in this field for the last few decades has opened up a new approach in design. Structural materials are no more homogeneous materials. Fiber reinforced concrete, composite materials and nano material based matrix in composites have been in focus. These materials provide a whole lot of additional features, like directional strength, better tensile strength and less weight for higher stiffness. However, these novel material compositions also call for an effective health monitoring in place. With the advancement of MEMS sensor technology, deploying a large number of sensors on a structure can be achieved. In some composite structures, sensors can be embedded too. The limiting factor turns out to be the power supply, which has to be provided by an autonomous source, converting the vibrations of the structure.

6.1 Satellite launch pads

A satellite launch pad is subjected to acoustic vibrations and input frequencies of range 20 to 2000 Hz. Launch of a satellite creates intense structure-borne vibrations. Structural resonance does happen, since wide band excitation happens due to the acoustic environment.[31] The structure also experiences shock loads of variable frequencies.. This wide band vibration spectrum can be effectively used for energy harvesting.

6.2 Bridges

Dynamic characteristics of large civil structures is a function of humidity, intensity of wind, temperature and the moving traffic. Effect of moving vehicles can modulate the natural frequency of a bridge. Concrete bridges generate 20–200 Hz) structure-borne noise due to the vibration of bridges.

Hence it is evident that a wide range of vibrational frequencies are present on different designs of bridges, during their operation at various ambient conditions.

6.3. Roads

The continuous flow of vehicles, applying different impact loads generate vibrations that can be suitable for energy harvesting. The long stretches of road can be integrated with piezoelectric elements and the associated electronics. Considering the continuous vibratory loads, a high amount of charge can be collected.

6.4 Dams

Structural elements in a dam are constantly experiencing varying loads due to the water pressure. This variable load can be the input for the energy converter, and in turn can power the sensors for its health monitoring.

6.5 Other civil structures – test stands etc.

Land based structures for simulating various loading scenarios make an important module in many development projects in engineering. These structures do experience loading cycles and vibrations during the simulation tests. These conditions make it absolutely necessary to monitor the health of the structures. At the same time, autonomous power source can be designed, utilizing the inevitable vibrations present on the structure.

6.6 Multi functional approach in using piezoelectric materials

Piezoelectric material functions as an effective vibration energy harvester as well as an extremely sensitive vibration sensor. A typical sensor circuit is given in figure 5.

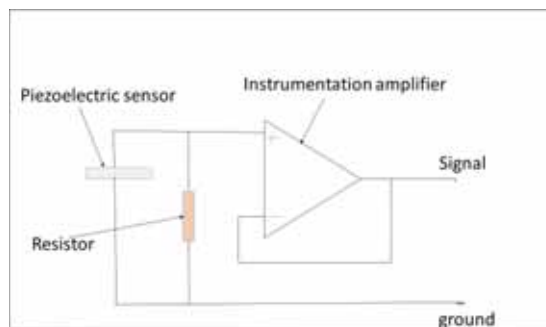


Figure 5. Piezoelectric sensor circuit

PZT sensors have high elastic modulus, brittleness and low tensile strength. The material is mechanically isotropic. Piezoelectric sensors are very sensitive to dynamic loading. Hence as the structure is instrumented for energy harvesting, it can also be integrated with piezoelectric sensors for health monitoring. This approach of using similar sensors will lead to an optimum design. Both the sensor and the harvester can be integrated in the MEMS design.

7. Conclusions.

Recent developments in structural health monitoring in various fields including civil structures, lead us to the most critical aspect of providing a sustainable power source. This important need can be addressed by energy harvesting from the structures / ambience. This paper has reviewed various attempts and results reported and their salient features. The research has been linked to the versatile PZTs and different lead free materials.

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Finding Pathways to Resilience in the Georgia Basin: Understanding Risk Vancouver 2017

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Abstract:

Understanding disaster risk is an important starting point for building community resilience. To increase the capacities of stakeholders to act before a disaster, we must increase the quality of, and access to integrated risk assessments. These assessments form the foundation for reducing systemic vulnerabilities, minimizing future losses, and improving the resilience of communities exposed to hazards.

Acting on this imperative, an interdisciplinary group of stakeholders staged a community symposium, Understanding Risk Vancouver 2017, to explore integrated, place-based strategies that promote disaster resilience in the Georgia Basin region of southwest British Columbia. The goal was to harness the global platforms of the United Nations' Sendai Framework for Disaster Risk Reduction and World Bank's Understanding Risk community of practice to build on and make linkages across current local and regional initiatives.

Refocusing the conversation from knowledge (of local hazards) to action, symposium discussions were concentrated on developing policies and strategies that could be taken to reduce disaster risk and increase community resilience. The group also evaluated a set of risk and resilience indicators, which can help shift the conversation. Indicators were from a range of categories: community resilience, lifeline resilience, building performance, social vulnerability, physical vulnerability, hazard potential and public safety.

The symposium produced a list of 34 recommendations covering four main topics: risk governance and funding; risk communication and education; data, mapping, modeling and tools; and buildings, codes and construction. A core subset of these recommendations are related to linking resilient building and infrastructure design with up-to-date hazard mapping and performance-based codes.

Participants expressed significant interest to establish a roundtable to periodically report progress on actionable strategies and initiatives for disaster risk reduction in the region. This mechanism would foster the increase in knowledge and capacity for disaster risk reduction that has been called for in the Sendai framework and elsewhere.

Keywords:

Disaster risk reduction, resilient buildings, resilient infrastructure, earthquakes, floods

1. Introduction

With the increasing costs associated with natural hazard events around the world [1], it has become apparent that new approaches are required to reduce risk and build resilience at neighbourhood and regional scales. Previous approaches to assessing and reducing risk have typically been targeted at the parcel or local authority level, and on a single-hazard basis. This has led to gaps between the different sectors that construct elements of the built environment, the qualified professionals that certify unique elements as 'safe for use intended', and the asset managers who work to reduce risks in the

subsets of infrastructure they manage. This historical, fragmented approach has driven the incremental accumulation of disaster risk in Canada's built environment, which has been exposed by recent natural hazard events, e.g. the 2013 floods in Southern Alberta [2] and the recent 2017 British Columbia wildfire season [3].

The gradual accumulation of disaster risk over time, along with ineffective management of that risk, are both obstacles to community resilience. The need to overcome these obstacles has become acute – particularly in the face of increasingly frequent and intense natural hazard events associated with a

changing climate. Recent, charged debate over the proposed location of a major new hospital in Vancouver, British Columbia (e.g. [4], [5]), reflects this urgency.

Understanding disaster risk is an important starting point to overcome these obstacles and build resilient communities. To increase the capacities of stakeholders to act before a disaster, we must increase the quality of, and access to integrated risk assessments. These assessments form the foundation for reducing systemic vulnerabilities, minimizing future losses, and improving the resilience of communities exposed to hazards.

Acting on this imperative, an interdisciplinary group of stakeholders staged a community symposium, Understanding Risk Vancouver 2017 (UR+ Vancouver), to explore integrated, place-based strategies that promote disaster resilience in the Georgia Basin region of southwest British Columbia (Fig. 1). The goal was to harness the global platforms of the United Nations' Sendai Framework for Disaster Risk Reduction and World Bank's Understanding Risk community of practice to build on and make linkages across current local and regional initiatives.



Fig 1: Metro Vancouver, part of The Georgia Basin region of southwest British Columbia, includes over 20 local authorities exposed to a range of natural hazards including river flooding, storm surges and earthquakes.

In this paper we describe the UR+ Vancouver symposium and the outcomes relevant to green civil engineering, including:

- The event, its scope, participants, and the nature of discussions held;
- The need for and the importance of: (1) resilient buildings, and (2) resilient lifelines; and,
- Potential next steps to increase the quality of, and access to integrated risk assessments – including roles for civil engineers to contribute to this effort and improve the resilience of the communities in which they live and work.

To put this discussion in context, we first explore the motivations behind UR+ Vancouver.

2. Motivation

The ultimate goals of disaster resilience planning are to save lives, protect property, promote socioeconomic security, and preserve the environment. These are among the most important responsibilities of government agencies at all jurisdictional levels. While the intent is clear, there are political challenges in implementing disaster risk reduction measures that draw scarce resources away from more immediate public policy issues. These challenges are compounded by a growing recognition that current practices of risk reduction through mitigation measures alone can in some cases have the unintended consequence of increasing levels of exposure and vulnerability by promoting a false sense of safe development (e.g. widening and raising dikes that may ultimately come to fail, meanwhile, increasing the density of assets behind them).

National policy guidelines for emergency management in Canada recognize the importance of disaster resilience planning at the community level. Although progress is being made to refine the scientific knowledge and methods needed to analyze and evaluate societal risks, there are still significant challenges in understanding how to incorporate this information into the broader context of planning and policy development. Specific questions that need to be addressed include:

- What are the likely impacts and consequences of natural hazards at the community and regional scales?
- What are the costs and benefits of investing in risk reduction and disaster resilience measures, and over what time horizons?
- What constitutes a tolerable threshold of risk for a specific geographic area or community, and who decides?
- Who bears the consequences of a natural disaster and how should collective risk be managed in the public domain?

There is an urgent need for a more holistic approach to disaster risk reduction planning in Canada -- one that makes evident the opportunities and socioeconomic benefits of incorporating disaster resilience into sustainable community development using integrated risk assessment and scenario planning methods; and including incentive based public-private programs that encourage proactive investments in risk reduction measures at local and regional scales.

Integrated risk assessment underpins an iterative process of planning and policy development in which knowledge about societal risk is transformed into actions that increase the capacities of a community to withstand, respond to, and recover from disaster events. It offers an evidence-based approach to disaster resilience planning that is informed by scientific analysis and modeling, and governed by community values that reflect who and what are considered vulnerable and in need of safeguarding

(i.e. analytic-deliberative process). Knowledge and understanding developed through analysis and exploration of scenario alternatives are used to evaluate policy alternatives based on a multi-criteria framework of indicators and performance measures that seek to balance trade-offs between growth opportunities and the constraints of development in areas exposed to natural hazards (Fig. 2).

Canada has an opportunity to promote the uptake of disaster risk reduction into sustainable community planning through strategic investments in research and open data initiatives that increase access to and capacities for integrated risk assessment at local and regional scales, and through incentive-based measures that are incorporated into the National Disaster Mitigation Program (NDMP).

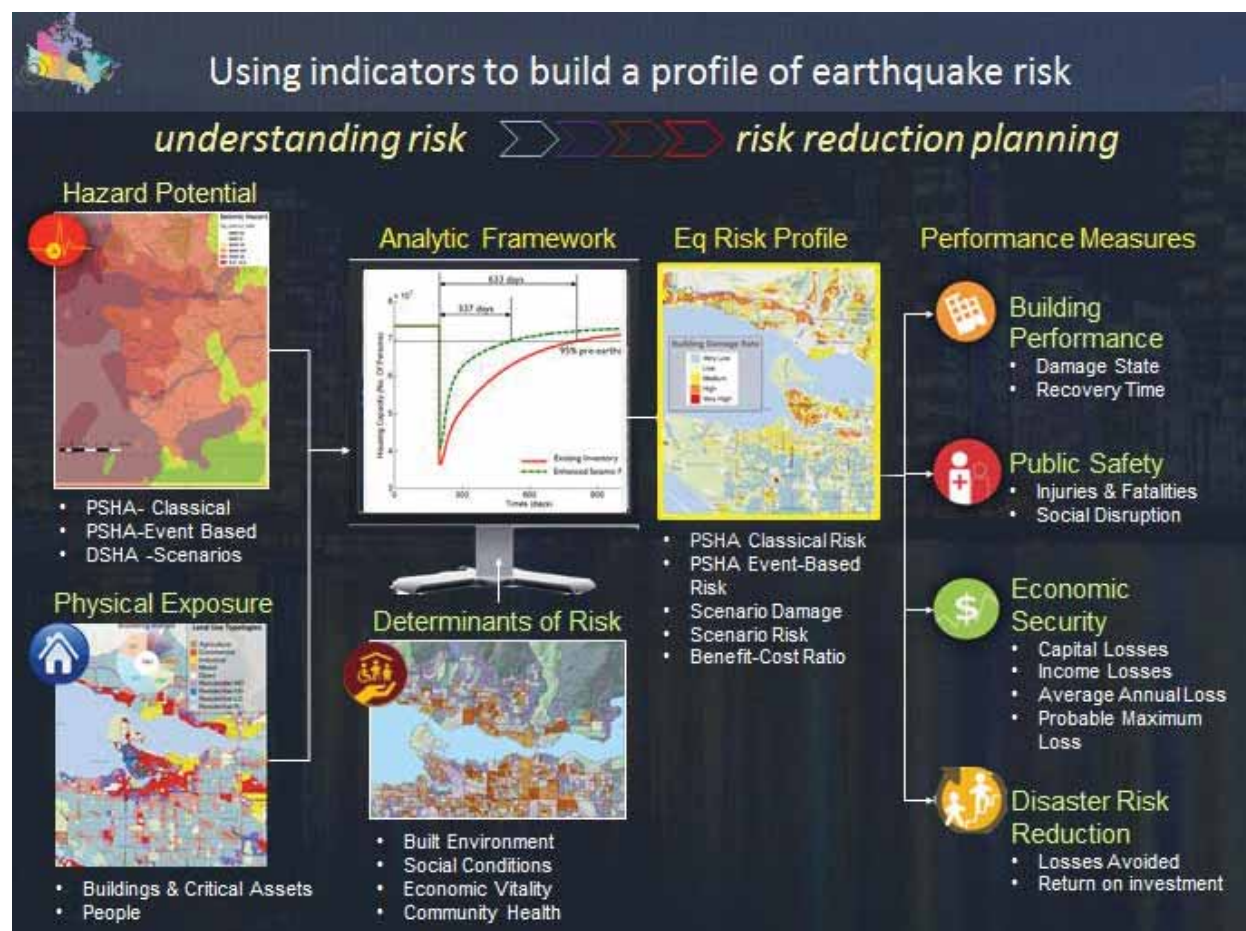


Fig 2: An effective understanding of risk (= hazard potential x physical exposure) is the necessary basis for development of a multi-criteria framework of indicators that enable effective policies for disaster risk management.

3. Understanding Risk Vancouver 2017

The UR+ Vancouver regional symposium, funded in part by Public Safety Canada, is an example of one such strategic investment. Held in Vancouver, British Columbia, from 29-31 March 2017, the symposium brought together an interdisciplinary group of stakeholders to explore integrated, place-based strategies that promote disaster resilience in the Georgia Basin region of Southwest British Columbia [6].

The organization of UR+ Vancouver was the result of collaborative efforts of multiple partners in various levels of government, consulting, professional organizations and academia. The goal was to harness the global platforms of the United Nations' Sendai Framework for Disaster Risk Reduction [7] and World Bank Global Facility for Disaster Risk Reduction (GFDRR) Understanding Risk community of practice [8] to build on and make new linkages across current local and regional disaster risk management initiatives. Adhering to the Understanding Risk format GFDRR had the advantage of being able to readily share symposium outcomes with the global risk community.

The symposium was preceded by a one-day kick-off workshop in February 2017 with a select group of experts from around the region to formulate key topics, explore potential session ideas, and develop the overall program for the symposium. Topics that were selected to form symposium sessions thus represented the most pressing issues and opportunities in risk identification, communication, and reduction in the region as identified by an interdisciplinary and local group.

The symposium itself included plenary sessions, panel discussions and six technical sessions focused on data gaps, risk communication, critical infrastructure interdependencies and resilience, empowering communities, resilient buildings, and disaster resilience finance incentives and innovations. Interaction and participation was stimulated during the symposium, and the input from ~200 participants (which included different levels of government, emergency management practitioners, researchers, planners, engineers, private sector organizations (e.g. critical infrastructure and assets) was solicited to guide development of policy proposals and strategies for risk reduction in the Georgia Basin and elsewhere in Canada (Fig. 3).

The symposium yielded 34 recommendations regarding policies and strategies for risk reduction.

Recommendations were grouped into the following categories:

1. Risk governance and funding;
2. Risk communication and education;
3. Data, mapping, modeling, and tools; and,
4. Buildings, codes, and construction.

A follow-on report submitted to Public Safety Canada captures these recommendations and the symposium outcomes in detail [9].

In sections 4 and 5 below, we focus on two symposium sessions and outcomes of interest to civil engineers: (1) buildings and (2) critical infrastructure systems.



Fig. 3: The UR+ Vancouver symposium concluded with a collaborative “resilience by design” planning challenge, and an open policy dialogue focusing on prioritizing recommended policies for disaster risk reduction in the Georgia Basin.

4. Resilient Buildings

A key subset of recommendations developed by the symposium participants focused on resilience of buildings (i.e. *buildings, codes and construction*).

Participants explored why we have the technical know-how to increase the performance of buildings to

withstand both flood and earthquake events but the lack of uptake of this knowledge for both retrofits and new buildings in the Georgia Basin. Increasing the resilience of buildings has the potential to reduce casualties, dollar losses, insurance claims, economic downtime and suffering (i.e. psychosocial stress) so what is holding us back from retrofitting or building better?

The participants further explored the most effective ways to increase resilience in different development scenarios (e.g. new development, redevelopments, urban vs. suburban contexts), and the benefits of using building codes or other forms of regulation and/or incentives (e.g. branded resilience ratings programs, or other incentivization mechanisms).

Another key question explored was: how do we work towards a shared understanding of building (or parcel)-level resilience given the current disparate fields of flood and earthquake-resilient design? In this session on resilient buildings, an expert group of conveners explored the above-mentioned issues, bringing their extensive engineering expertise to bear on the cross-disciplinary discussion.

Currently, the National Building Code of Canada (NBCC) requires buildings to be built to a life-safety standard. There is a desire to move beyond a life-safety standard and include Performance-Based Design (PBD) in the code that can reduce building damage and ensure post-event functionality. To help foster the adoption of this approach, a case needs to be made to the Canadian Commission on Building and Fire Codes - which also identifies financial implications. It is estimated that getting buildings to a point where they are designed to reduce or mitigate damage in relation to seismic hazard (as opposed to life safety) requires an incremental cost of between 1-4%, depending on structure type (a higher percentage for smaller structures). With current approaches, a lot of money is being spent getting older buildings to be retrofitted to a life safety standard, but we can do better than this. We have opportunities using the provincial Building Act, wherein local governments can propose variations to the building code with respect to seismic performance (e.g. using a performance based approach to achieve post-event functionality). If such a variation is approved under the Building Act, it can apply to the municipalities making the request as well as those choosing to opt in to the building regulation. We can also look to the National Research Council's (NRC) recent/emerging work on flood-related provisions; while seismic safety thresholds have been a part of the NBCC for several decades, flood-specific risk reduction measures have not previously been included.

A key challenge for improving building performance is that developers are not, in most cases, the building owners. Accordingly, the incentive or business case to build to a more resilient standard is often not there. Changing public perception around what the code provides (i.e. life-safety vs. functionality through a PBD) is a critical first step in generating consumer awareness and demand for better buildings which can in turn spur developers to meet those consumer demands. All levels of government should be involved in this. There is a lot to be learned from the dialogue and programs in the USA regarding incentivization (e.g. the work of the Multihazard Mitigation Council). There is a need to collectively demonstrate the importance of the 1-4% rise in upfront construction costs as compared to the huge amount of direct and indirect economic loss that we will be dealing with in the aftermath of major flood and earthquake events.

Case Studies

Various owners, regulators and stakeholders across the Georgia Basin are making efforts to reduce risk to buildings from earthquake hazards.

- The public schools retrofit program and Seismic Retrofit Guidelines 2nd edition (SRG2). The SRG Guidelines are an outcome of the extensive work that has been undertaken to retrofit British Columbia's public schools. This effort has provided a focal point for the scientific, academic and engineering communities to develop PBD standards for the retrofit of a subset of buildings.
- The 'Geotech on Demand' program in the District of North Vancouver helps building owners understand their buildings and site and available options to reduce risk. The District covers the upfront cost of having a high-level site inspection done of properties that are in risk zones. Any recommended mitigation work following the inspection is the responsibility of the property owner.

Challenges and Opportunities

Some of the specific challenges that symposium participants identified include:

- Advocating for better design and building the business case for additional costs of construction (1-4% for seismic PBD).
- Public awareness of what the code is providing (life safety vs. functionality).

- Large existing stock of buildings that is not built to seismic code (60-70%) in the Georgia Basin.

Specific opportunities include:

- Building on the BC school's program and SRG2 to expand to a wider set of buildings (e.g. province-wide civic assets, privately owned buildings).

Recommendations

Symposium discussions resulted in several, actionable strategies and policy proposals for buildings.

1. Support increased awareness of benefits of PBD for the public and government to increase uptake. The senior design professions (EGBC, AIBC) in BC should make a joint submission to government. This should happen as soon as possible to prepare for 2020 code changes. Increased awareness will lead to increased demand for PBD, and alignment can be fostered between governments and public.
2. Establish a single authority within government to move to a risk based approach dealing with a variety of natural hazards. This will facilitate the use of performance-based designs that will apply to a range of natural hazards and ensure that an approach for dealing with one type of natural hazard is not in conflict with the approach for another natural hazard. Provincial government, at the Deputy Minister level, with the support of various stakeholders including professional regulatory bodies for the design professions (EGBC, AIBC, ABCFP, CAB, BCIA). This will facilitate the use of performance-based designs which address natural hazards in a comprehensive fashion and avoid mal-adaptations across hazards.
3. Develop the financial and legislative framework to incentivize and facilitate the performance-based seismic retrofit of existing buildings. Municipal and provincial governments can set up a roundtable with Union of BC Municipalities (UBCM) such that representatives from professional associations and municipalities can discuss this and implement in an ongoing way. There is a need for incentives and a process for permitting retrofits designed using a PBD approach. Failure to do this will result in existing building stock being left vulnerable in the event of an earthquake or flood.

4. Develop the financial and legislative framework to incentivize and facilitate resilient new buildings. Like the above (Strategy 3), there is a need to develop a coordinated approach to building resilience for climate change, earthquakes, etc., that addresses both new and existing buildings.
5. Develop training programs for performance-based and risk-based design both at the undergraduate and professional level. Professional associations (APEGBC, AIBC, ABCFP, BCIA) and universities should develop a plan because there is lack of awareness and understanding of what performance based/risk based design is and how it is carried out.
6. Survey the public to understand what they expect and want from new and existing buildings when it comes to resilience (e.g. life safety performance, damage mitigation, etc.). Survey could be coordinated by the Building and Safety Standards Branch. Representatives from professional associations and municipalities meet with the Union of BC Municipalities to discuss a coordinated approach with the provincial government. There is a need to establish a shared understanding of risks and expectations regarding building performance.

5. Critical Infrastructure Systems

Critical infrastructure (CI) systems, also known as lifelines, provide for the movement of water, sewage, energy, goods and people on a day-to-day basis across the region, and form the backbone of the regional economy. In a major flood or earthquake, these systems are vulnerable to damage; moreover, failures in one system are likely to lead to failures in other, dependent systems. For example, dikes throughout the region provide a degree of protection to hundreds of thousands living in floodplains and are vulnerable to seismic events.

In a major disaster, not only would infrastructure damage cause social and economic disruption across the region, but functional infrastructure networks will be essential to emergency response and recovery.

Resilient infrastructure systems are essential for a resilient region. Infrastructure interdependencies and cascading impacts make lifeline resilience an important issue of shared risk in the Georgia Basin. As such, the UR+ Vancouver session, *Charting a Path toward Lifeline Resilience: Critical Infrastructure Interdependencies and Opportunities for Increased*

Disaster Resilience, explored these topics and looked beyond individual lifelines to examine critical infrastructure interdependencies.

Case Studies

Various critical infrastructure owners and stakeholders across the Georgia Basin are making efforts to reduce risk to critical infrastructure systems from flood and earthquake hazards.

- Metro Vancouver is seismically hardening its water and wastewater systems, and is considering flood hazard in new facilities' design and location.
- The British Columbia Ministry of Transportation and Infrastructure have developed *Disaster Response Routes* across the Lower Mainland, including recent initiatives on multi-modal response/recovery routes and "critical routes" in the provincial earthquake Immediate Response Plan (IRP). In the past, routes were not always designated in collaboration with partners or based on information about hazard and risk. There remains a need for coordination between emergency managers and infrastructure asset managers, so that efforts to strengthen and adapt lifeline infrastructure assets are made with a response/recovery perspective in mind.
- Emergency Management British Columbia has been developing a Critical Infrastructure Assessment Tool for local governments. This effort could be aligned with the Engineers Canada tool PIEVC.
- The City of Surrey, through its Coastal Flood Adaptation Strategy, is addressing flooding and sea-level rise risks to vulnerable infrastructure using the Engineers Canada PIEVCTM Protocol (Public Infrastructure Engineering Vulnerability Committee).
- The Fraser Basin Council, via the Lower Mainland Flood Management Strategy, has recently conducted scenario assessments of expected flood losses. Results highlight high costs, interdependencies, and regional significance of infrastructure vulnerability. These scenarios can be improved upon with greater degree of detail and looking at interdependencies.
- University-based researchers have completed several critical infrastructure interdependencies studies in the local context, including a current

study on maritime transportation and the fuel supply chain.

- Coordination committees, including the provincial Critical Infrastructure Steering Committee and the Integrated Partnership for Regional Emergency Management (IPREM) apply a high-level, systems view to critical infrastructure.

Challenges and Opportunities

Symposium participants were polled regarding their views on infrastructure resilience in Metro Vancouver. Overwhelmingly, participants agreed with the statement "There are some problems" (71%). Few considered that "We are on the right track" (18%) and none indicated that "We are doing well".

When asked about the most important gaps preventing critical infrastructure resilience, most participants identified: (1) coordination across levels of government, and (2) having vulnerability information shared among critical infrastructure providers. Other gaps or needs included linking infrastructure providers with available support, and understanding risk (especially earthquake risk).

Some of the specific challenges that symposium participants identified include:

- Gaps between the federal, provincial and regional governments' emergency planning, priorities, and expectations.
- Reluctance among CI providers to share details of plans and strategies makes it difficult for organizations that are dependent on CI to act and plan.
- Limited institutional memory due to staff turnover makes long-term learning challenging.
- Clear expectations need to be conveyed from the public sector to the private sector, so that the private sector knows what the public sector might need in an emergency and can plan accordingly.
- CI owners are not using programs such as HAZUS or publicly sharing related information. When information is shared, details are not provided due to security concerns, the lack of detail makes the data hard to use.
- Institutional communication isn't mapped, which makes it difficult to know who the key actors are

and how (if at all) they are communicating with each other.

- Accounting for interrelated and secondary risks (e.g., an earthquake that causes subsidence, dike damage, and other impacts that exacerbate flood risk).

Specific opportunities include:

- Communication among critical infrastructure owners and stakeholders can be more transparent and robust.
- Tools for assessing and understanding critical infrastructure risks are available but not being utilized collaboratively.
- Minimize duplication of efforts (e.g. between agencies).
- Collaboration between decision-makers, emergency managers, and others within organizations, such as sustainability groups can promote synergies with other organizational objectives besides disaster risk reduction (e.g. a low carbon resilience approach).

Recommendations

Symposium discussions resulted in several, actionable strategy and policy proposals for critical infrastructure.

1. Develop networks for CI coordination. Coordination is essential for understanding roles and responsibilities of different organizations, including CI providers and multiple levels of government. This needs to be done efficiently and effectively. Networks should identify a point person in each organization and maintain this contact in the event of staff turnover. Networks should identify where there are coordination gaps between organizations.
2. Develop forums for sharing CI information. One possibility would be a dedicated CI stream at the Emergency Preparedness and Business Continuity (EPBC) conference every November, or to have another focusing event like the 2010 Olympics. This would capitalize on a forum where most stakeholders are already present. Another possibility is a forum hosted by a municipality (e.g., City of Vancouver) to convene representatives from diverse sectors. Another option is to convene an annual UR+ event. Meeting forums should be complemented by a

repository of records, so that institutional knowledge can be maintained even with staff turnover.

3. Educate the public about CI risk. As with risks from buildings in earthquakes, risks from CI are not well understood by the general public or decision-makers. It is important to help the public develop realistic expectations of lifeline disruption in a major earthquake or flood. The District of North Vancouver's approach (connecting with the public through open data and narratives) provides a useful model. Disasters in other regions present public education opportunities, especially if interest can be maintained.
4. Develop tools and knowledge for analyzing regional costs and benefits of CI risk reduction investments. Existing tools should be used to better understand and assess regional risks from CI disruption in a major earthquake or flood, and new tools should be developed to address gaps that require more complex assessments. Better understanding of the interactions between flood and earthquake hazards is especially needed.
5. Make the business case for CI risk reduction. Gaining the necessary funding for CI risk reduction investments will require convincing decision-makers about the long-term value of these investments. Analysis of costs and benefits is similarly important for making the best use of available disaster risk reduction funds. Evaluating risk from a multi-hazard perspective (especially considering earthquake and flood risks together) can help make risk reduction investments more appealing, and multi-hazard mitigation strategies may be more cost-effective than single-hazard investments.

6. Policies

The UR+ Vancouver concluded with participants voting on the various policies proposed during the symposium to identify the most promising strategies for disaster risk reduction in the Georgia Basin. These included:

- Encouraging multi-hazard considerations for retrofits (32.0%). It is easier to justify the cost of a retrofit when you are protecting against multiple hazards.

- Hosting forums for people from diverse sectors and organizations to explore and clarify roles, such as a CI track at EGBC conference (25.8%).
- Establishing a communication network that highlights decision-makers (21.7%). This could be a database of key local stakeholders (contact info) to facilitate direct conversation across traditional organizational and professional boundaries.
- Supporting owners of infrastructure and buildings to understand codes and their implications (20.6%). This could be public awareness campaigns, e.g. regarding the current life-safety standard of NBCC and the interdependency of critical infrastructure.

7. Next Steps

UR+ Vancouver was a starting point for integrated disaster risk reduction in the Georgia Basin. Participants expressed a strong interest to reconvene periodically during an annual roundtable or conference. This would give stakeholders a mechanism to report back progress on actionable strategies and initiatives for disaster risk reduction in the Georgia Basin. It would also foster the increase in knowledge and capacity for disaster risk reduction that has been called for in the Sendai framework and elsewhere.

8. Conclusions

A regional community symposium, Understanding Risk Vancouver 2017 brought together an interdisciplinary group of stakeholders to explore integrated strategies to promote disaster resilience in the Georgia Basin region of southwest British Columbia. The impetus for this symposium was a gap between current knowledge on disaster risk reduction and action: existing approaches to assess and reduce risk in relation to infrastructure and the built environment are inefficient to address multi-hazard risk at the neighborhood and regional scales, and as such inefficient to minimize potential future losses.

Whereas previous approaches to assess and reduce risk were typically targeted at the parcel or local level, it is now clear that we must look beyond individual buildings and singular pieces of infrastructure to increase regional resilience. This requires taking a 'systems', or integrated, interdisciplinary perspective and approach; which should be done by looking at the

broader context in which individual assets sit, within a neighbourhood or regional context.

The symposium yielded multiple specific recommendations for actionable strategies and policies focused on resilient buildings and infrastructure. The participants further identified various general collaborative and transdisciplinary efforts to reduce risk and increase resilience in the region, including:

- Developing shared and open risk assessments that explore system interdependencies;
- Stimulating a multi-hazard approach to developing policy and guidelines regarding elements of the built environment (i.e. earthquakes and water-related hazards are the recurring concerns in the Georgia Basin);
- Addressing both existing and new elements of the built environment in a coherent manner;
- Working collaboratively to incentivize the needed risk reduction and resilience building decisions, from the homeowner, to regional scale using insurance, lending practices, and creative local area development; and
- Establishing a roundtable to periodically report progress on actionable strategies and initiatives for disaster risk reduction in the region. Such a mechanism would foster the increase in knowledge and capacity among stakeholders for disaster risk reduction that has been called for in the Sendai framework and elsewhere.

Acknowledgements

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We thank the individual organizers and volunteers for their time and effort in putting together the symposium. We especially acknowledge the contribution of Susanna Haas-Lyons, who facilitated the dialogue.

Finally, we thank the participants for making UR+ Vancouver a success and helping to advance integrated disaster risk management across the Georgia Basin.

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VR-based crane operation planning using head-mounted display

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Abstract:

Industrial construction projects require large-scale lifting equipment for handling of materials and fabricated components, temporary facilities for material storage, and assembly tools to support erection activities, and it is often challenging to operate the crane in highly congested space to perform these lifts. This paper presents a novel method to deploy virtual reality (VR) using 3D VR headsets in assessing possible collisions when planning heavy industrial crane lifts. Using the HTC Vive VR headset, the user can “visit” the virtual job site and identify safety hazards as well as any possible collisions. This research uses as a case study a vessel replacement project at an oil refinery. The lifting operation uses two cranes to perform the task in a site congested due to existing pipe and rack structures in the vicinity. Furthermore, the two-crane lift operation is required to be performed above operating pipelines. Crane operation scenarios are created using an HTC Vive VR headset which simulates real-world site activities in a virtual environment, such that the user can identify potential collisions before the actual process begins. The system can also be utilized to train riggers, crane operators, or ironworkers on assigned tasks.

Keywords:

Virtual reality, Head-mounted display, Collision detection

1. Introduction

In recent years, Virtual Reality (VR) has been making headlines in the tech industry, especially in entertainment and gaming. VR represents real-world objects in a computer-simulated environment, providing the user a realistic experience with interactive 3D visual representation [26]. VR headsets are now being widely used in entertainment and gaming, and are beginning to see some limited architectural applications, though only to visualize the design. Furthermore, VR has been used in workforce training applications such as improving skills and safety in performing surgeries [1, 2], in anesthesiology [3] and for laparoscopic and cardiovascular procedures [4]. Head-mounted display (HMD)-based VR systems in the mining industry have yielded improved training results and have shown the potential to play a more important role as a training tool for mine safety [5]. In a recent study, mine workers trained using VR headsets reported positive effects of VR-based training even up to three months after their training session [7]. These studies demonstrate the potential of VR to improve the jobsite planning process with its capability to visually convey conflicts and other issues [26].

In this paper, we propose an HMD-based VR system that enables the user to be immersed in a congested heavy industrial jobsite. Using realistic rendering in a game engine, we are able to create crane operation scenarios with the support of existing 3D modelling geometries. Also, a data collection feature is included

to support further analysis of the user's virtual performance of the lifting operation.

2. Relevant Research

Crane lifts are unique among heavy equipment operations as they require a relatively large workspace and have a significant impact on the safety and productivity of the entire project [8]. Furthermore, failure to identify possible collisions in a confined workspace can lead to catastrophic accidents and project delay. Training the lift crews in a virtual environment can improve the collaboration among crane lifting crew members and improve operator proficiency [9,10,11,12,13,14]. Shapira et al. (2008) found that the use of a visualization system to support tower crane operations significantly improved safety and productivity (26% overall operational time savings) [15]. Kang and Miranda (2004) created a crane operation visualization system with motion-planning algorithms which finds collision-free and time-efficient paths for erecting modular industrial projects, resulting in an accurate and detailed schedule for erection processes [16]. The virtual safety training system developed by Guo et al. (2012) allows multiple users to collaborate and interact within a virtual construction plant; they demonstrated that the platform improves the process and performance of the safety training involved in the case company's operations [17]. A virtual training framework developed by Fang et al. (2014) integrates building information modelling (BIM) and real-time location tracking technology in a virtual environment to

construct as-built construction site environments for heavy lifting tasks; it was shown to effectively assess and improve crane operator proficiency in an actual construction project [18]. Li et al. (2012) created a multi-user virtual safety training system for tower crane operation that allows trainees to learn precise crane dismantling procedures in a risk-free environment; the survey results they presented showed that the trainees under that system generally learned better than those trained using the traditional method.

Despite much research on the adoption of VR-based training technologies for crane operation, the application of VR training in practice is not very common due to the fact that it is time-consuming and computational expensiveness to represent and reproduce an as-built virtual work environment for training purposes. Furthermore, historically VR hardware has been prohibitively expensive. However, with the release of new-generation, low-cost HMD technology, it is now more feasible to achieve realistic immersive experiences for the user [27]. In the present study, a new low-cost crane operation training framework is developed using HTC Vive and Unity 3D game engine.

3. Research Methodology

This research proposes a framework for training on crane lift operations in congested worksites, using the case study of a vessel replacement at an oil refinery. The case study involves a highly congested site (as shown in Fig. 1) in which it is very challenging to operate the crane to perform the lifting sequence without colliding with existing structures (i.e., Structures A, B, and C in Fig. 1). In this case, from the origin of the boom, structure A has a clearance of about 89 ft., Structure B has about 32 ft. of clearance, whereas structure C has a possibility of colliding with the Y-guy of the crane when increasing the boom angle to avoid a collision with Structure B. It is thus crucial to find an acceptable trajectory (Fig. 2) and crane movement sequence in order to avoid possible collisions. By developing a VR training system, moreover, it is possible to perform low-cost dry runs to train the operating team in a realistic manner.

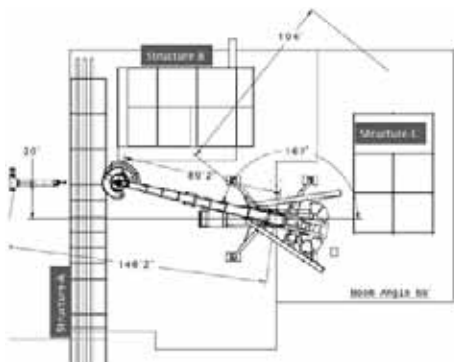


Fig. 1: Site plan of the crane operation

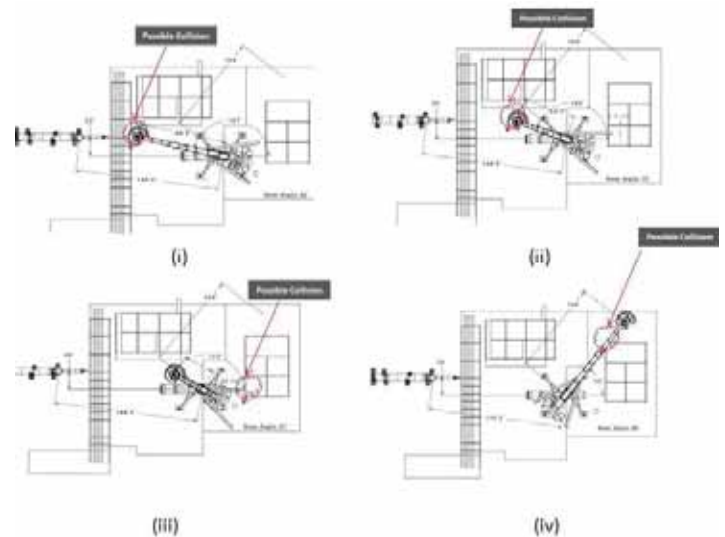


Fig. 2: Trajectory analysis of the crane operation

A major objective of implementing VR in operator safety training is to expose operators to potential hazards of collisions in a risk-free manner and help them to develop timely and reasonable accuracy to move heavy modules according to an efficient lifting sequence, avoiding possible collisions with existing modules. The aim of the present research, then, is to improve the crane operation with the help of VR headset technology. It provides a testbed for crane operation site safety in order to analyze operators' learning outcomes in a virtual environment, and consists of a hardware and software side. At present several major companies are producing PC-based high-end VR HMDs which are commercially available to consumers and which deliver a highly immersive virtual experience. HTC Vive in particular comes with room-scale tracking, with improved motion tracking capability, and with two hand controllers to track objects in a room-scale VR environment via passive laser diodes. It enables users to use grab gestures for picking up virtual objects and to interact with their surroundings.

The software element of the proposed framework requires a game engine that can simulate the physics of the virtual environment. Unity 3D game engine, developed by Unity Technologies, is selected for the proposed framework because of its user-friendly interface, rich store of assets, versatile platform access, and C# programming language scripting support. Fig. 3 depicts the workflow of the proposed framework. (In the case study, all the site information was collected from the client in the form of PDF drawings.) By analyzing the site drawings, existing structures prone to collision during vessel replacement operation are identified and 3D models are generated in 3ds Max maintaining full-scale dimensions. From an existing crane database, a 3D model of the operating crane is imported to the game engine with appropriate texture.

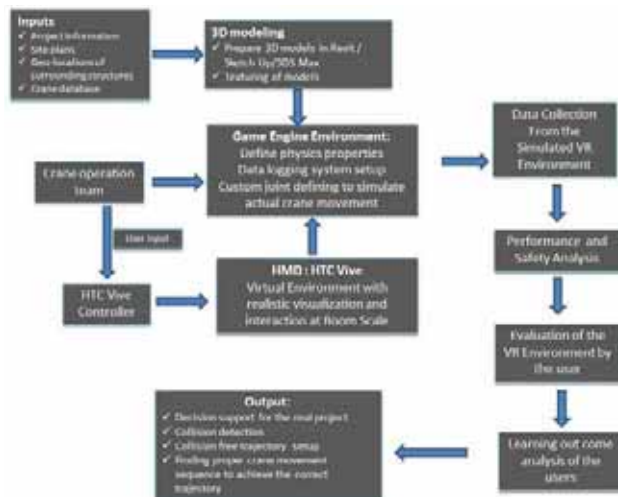


Fig. 3: VR framework for crane operation design

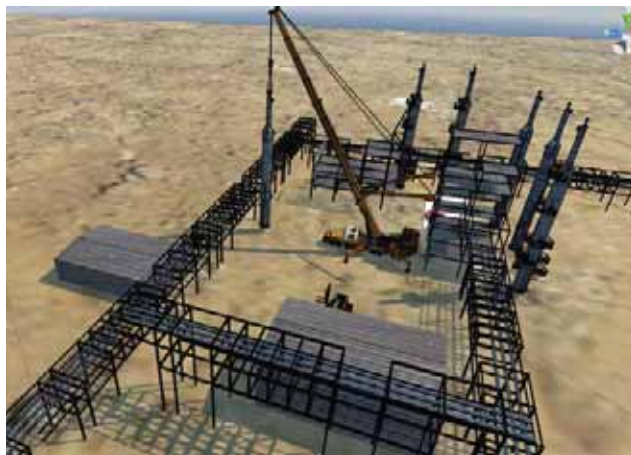


Fig. 4: Case study scenario setup following the site plan

To ensure proper learning outcomes using this VR application, a game logic as defined by Gamification / Serious Game Theory is followed in the proposed system. Gamification, defined as “the use of video game elements in non-gaming systems to improve user experience and user engagement” [12] is a standard technique used across a variety of disciplines to influence people to engage in particular targeted activities [19]. Application of game mechanics to create a virtual learning environment following gamification theory, it should be noted, has been highly successful in terms of its impact on training in specific skills as reported in previous studies [6,20,21,22,23,24,25,28]. Five major gamification attributes are implemented in the present application, as shown in Table 1.

Table 1: Attributes of gamification theory used in the proposed framework

* Attribute Category	* Definition	Implementation of gamification
Action language	The device and interface, which acts as communication medium between the user and the virtual environment itself	To participate in trial runs of this system, users are required to use the buttons of the controller
Control	The user's freedom to influence virtual elements existing in the system	The user can control crane movement with real-time location tracking
Environment	The illustration of the physical environs of the user	User is immersed in a virtual environment complete with worksite features and equipment
Immersion	The degree of realistic representation to give the user a perceptual experience	The system is capable of producing 360° virtual workspace with high-quality graphics
Rules/Goals	Clearly defined objective to achieve effective learning outcome	The user has to move a module without clashing with surrounding structures

*Source. Attribute categories and their definition was adopted from by Bedwell, Pavlas, Heyne, Lazzara, and Salas (2012). [12]

Fig. 4 shows the proposed framework in use. As can be seen, the user faces three surrounding screens while wearing the HTC Vive. Other operators can view a projected version of the VR rendering on the surrounding screen, enabling simultaneous instruction. The HTC Vive light house tracks the headset position and the controller's movement and provides real-time input to the game engine, which enables movement and interaction with objects in the VR environment. When a user wears the headset, they experience 360° immersion in the virtual worksite and can walk through the entire site using the right controller. The user can also control their movement using the left controller's touchpad and grip button (Fig. 5).



Fig. 4: Crane operation design in VR environment



Fig. 5: User interaction button definition

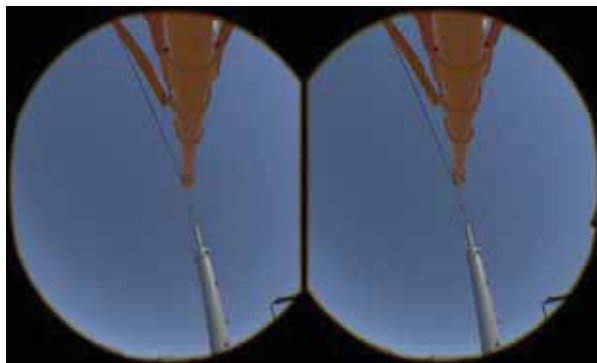


Fig. 6: Real-time view from operator perspective while conducting trial run

The system is capable of detecting collision events and locations of lifted modules at different stages of crane operation. While the virtual crane is in operation the system tracks the boom coordinates, such that the user performance can be evaluated by comparing with a predefined trajectory determined by performing trial runs of the system where successful lifting of the

vessel has been achieved (i.e., without encountering any collisions). In the case study the site is highly congested, with the crane operation subject to two possible types of collisions: (i) while rotating the boom, the lifted object may collide with an existing structure on the project site (Fig. 7), or (ii) the Y-guy of the crane may collide with Structure C (Fig. 8) if the crane boom is not raised following a certain rotational sequence. Focusing on spatial conflict issues in this virtual crane lifting simulation, the proposed framework uses two possible major incidents as the basis for defining rules: close proximity to existing structures, and finding a proper lifting sequence for crane operation, which in turn entails teaching the user logical sequences of when to rotate and when to alter the boom angle to avoid collisions.

A test run of the system with undergraduate university students showed that interaction in the VR environment helped them to identify key aspects of operating a crane in a real jobsite, and that it is a viable option for heavy lifting operation management.

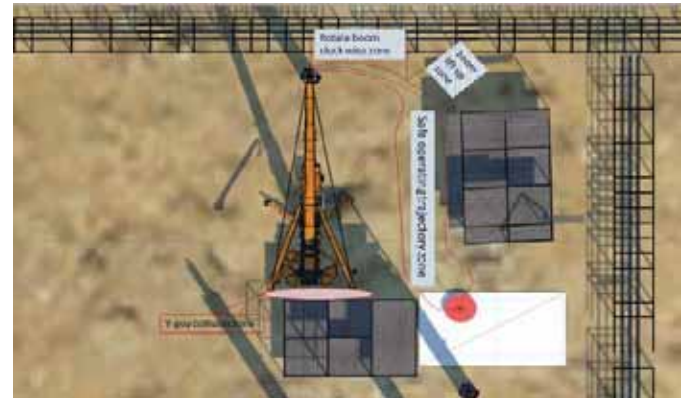


Fig. 7: Possible collision event

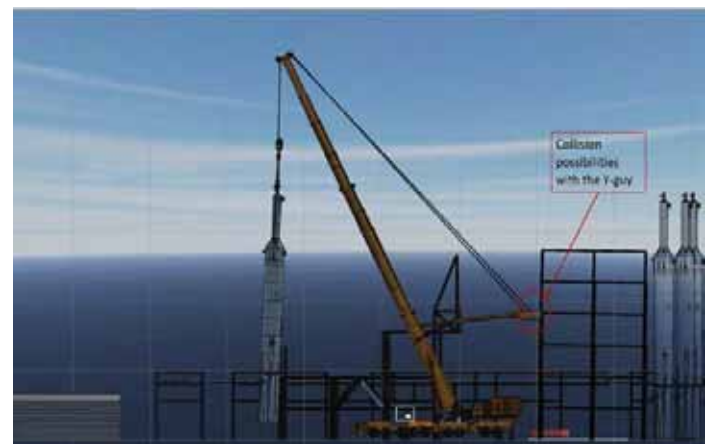
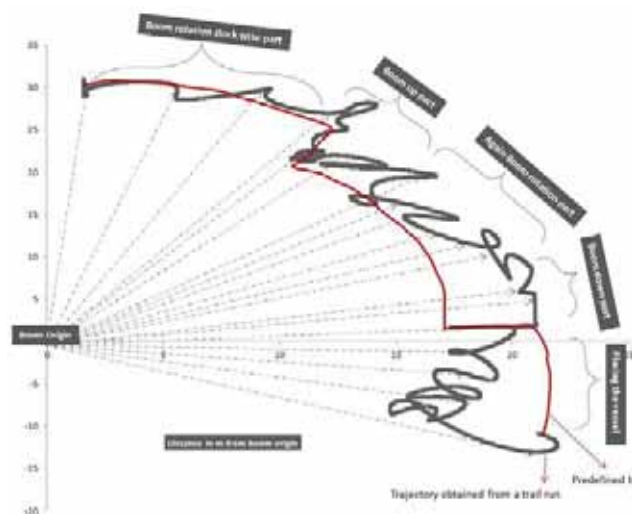


Fig. 8: Collision of Y-guy with structure C

4. Results and Discussion

Assessment and analysis of site constraints in heavy industrial crane operation is an important task influencing safety and successful project completion. By using this system, the site crew can practice the operation in a realistic manner incorporating actual site conditions before the actual task begins, experiencing the challenges they may face while operating in the field. They can train on how to move the crane according to a predefined logical sequence to avoid collisions. Using state-of-the-art digital 3D modelling software and commercially available VR headsets, it is possible to create a realistic worksite for the user at a low cost and with a feasible amount of development effort.

The data collected from test runs can also be used later for analyzing and revising operational plans. Fig. 9 is a plot of the data logged into the system while performing a test run in the developed VR environment. It shows the pattern of the different crane movement events at various locations, giving a relative evaluation performance of the user performing work in the virtual environment. Performing the test run with a larger group of people, it can be possible to validate the matrix of safety performance that can be incorporated within this framework. In future work we will test larger groups ($n > 20$) of students and crane operators in an extensive experimental study.



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Hygrothermal field testing of multi-functional wood fibre panels for residential buildings

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Abstract:

In recent years, high-energy-performance building envelopes have garnered increasing global interest. This research investigates and evaluates the long-term hygrothermal performance of innovative multi-functional panels (MFPs) in various wall assembly configurations for residential buildings under varying climatic conditions. The MFPs under investigation combine two layers of wood sheathing with other elements, such as wood fibre and Extruded Polystyrene (XPS), as additional external layers to conventional light wood-frame wall assemblies in order to improve the overall energy efficiency of conventional wall assemblies. For this purpose, two identical demonstration buildings are built for in-situ testing—one located in the cool continental climate of Edmonton, Canada, and the other in the humid coastal climate of Vancouver, Canada. The two innovative MFPs, in addition to a conventional wall assembly, are placed at both north and south façades of each of the demonstration buildings. Sensors are installed on each wall assembly under controlled indoor climatic conditions to monitor temperature, moisture content, and heat flux at the inner, middle, and outer layers and at three different vertical levels for each wall system. The indoor climatic conditions are maintained by installing a floor heating system, an air conditioner, and a rotating fan for temperature circulation. Also, each demonstration building is equipped with a weather station to monitor solar radiation, precipitation, atmospheric pressure, outdoor temperature, and relative humidity, among others. Results from this study demonstrate the effect of various weather conditions on the two innovative MFPs in comparison with conventional wall assemblies and also determine the long-term hygrothermal performance of the MFPs under investigation. This ongoing study will provide a practical guideline for the application of wood fibre—an environmentally-friendly and recyclable material—for the North American housing market.

Keywords:

Multi-functional panel, Wood-frame wall assembly, Thermal resistance, Long-term field monitoring, Energy efficiency.

1. Introduction

Professionals worldwide agree that energy is one of the key factors influencing efforts to achieve sustainable development [1]. Buildings account for 30% to 40% of the total energy use in North America [2]. Therefore, improvements in the building sector will have positive effects in other sectors, notably the power sector, because over half of the electricity consumed today is used in buildings [3]. If a building is energy-efficient, durable, and provides comfortable and healthy indoor environment for occupants, it can be classified as a high-performance building [4]. Using high-performance materials for the building envelope can increase the energy efficiency of the building. In this context, building professionals seek thermal-effective and humidity-resistant materials. Thus, to ensure these materials perform effectively, a long-term hygrothermal evaluation is recommended.

In Canada, buildings produce 17% of greenhouse gas emissions, including emissions from generating electricity for use in buildings [5]. In this context, in the past decade, governments around the world have focused on regulations to improve the energy efficiency in buildings. Between April 2007 and March 2012, the ecoENERGY program was adopted into

Canada's Economic Action Plan. Notably, the program supported technology and innovation for projects in Aboriginal and Northern communities [6]. Another Government of Canada initiative, the Energy Star program, promotes energy-efficient technologies and, since 2005, has administered certification for new energy-efficient houses [7].

Building energy performance is a widely-discussed research topic. Awad et al. (2014) investigate the long-term thermal and structural performance of mid-rise wood-frame systems. In their study, staggered and I-Joist systems, in addition to a conventional wall system, are tested for in-situ long-term structural and thermal performance [8]. Li et al. (2016) conduct a long-term monitoring study of hygrothermal performance of five wood-frame wall systems using various types of insulation. In their study, field testing and occupied conditions are applied [9]. Sassine et al. (2016) propose a method based on complex Fourier for thermal characterization to determine thermal capacitance and conductivity of the wall; sensors are installed to measure the indoor and outdoor temperature and outdoor heat flux with the data being collected every 20 minutes [10]. An enclosure's thermal performance of a house should be optimized to be considered energy-efficient [11].

Despite the number of studies being conducted in this area, the current ongoing research project presented in this paper contributes to the investigation of the hygrothermal performance of two innovative and environmentally-friendly MFPs in addition to a conventional wall assembly based on long-term monitoring.

The evaluation involves real-life scenarios in the built test huts. ASHRAE-90.1 Standard (ASHRAE, 2007) specifies the energy performance requirements for buildings for various climate zones. The present research aims to evaluate the performance of materials in two climatic conditions (Edmonton and Vancouver) and orientations (north and south).

2. Experimental Setup and Implementation

Two test huts are built in different climate conditions in Canada. The first test hut is located in the humid coastal climate of Vancouver, British Columbia, and the other is located in the cold climate of Edmonton, Alberta. Both demonstration buildings are identical in size and geometry: 7.62 m x 3.66 m (25 ft x 12 ft), and are identically oriented toward the sun's path.



Figure 1: Test huts in (a) Vancouver; (b) Edmonton

Two innovative multifunctional panels are used to build the test huts. The A-type MFP consists of 6.4 mm (1/4 in) OSB, 25 mm (1 in) Extruded Polystyrene (XPS), and 6.4 mm (3/8 in) OSB; the B-type consists of 6.4 mm (3/8 in) OSB, 40 mm (1 1/2 in) of wood fibre insulation, and 6.4 mm (1/4 in) OSB.

Both panels are installed on the exterior north and south walls of each demonstration building. A specific configuration for the installation is chosen to analyze the hygrothermal performance of the materials under investigation. For example, each wall consists of five panels: 2 A-type, 2 B-type, and 1 C-type wall assemblies, where the C-type assembly represents a conventional system with no MFP attached to its exterior side such as in the case of the A- and B-type wall assemblies. Figure 2 is a representation of the position of the panels and their orientations. For instance, in Figure 2, the letters N and S indicate north and south orientations of the wall assemblies,

respectively, the numbers 1 through 5 indicate the order of the wall panels from west to east, and the letters A, B, and C identify the panel type.

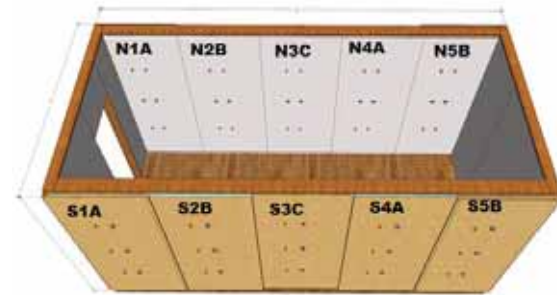


Figure 2: Nomenclature of each panel indicates orientation and type.

For the hygrothermal evaluation, nearly 200 sensors are installed in each test hut: 132 independent temperature sensors, 176 point moisture measurement (PMM) with temperature sensors, 30 cavity relative humidity and temperature sensors, 40 heat flux sensors, 8 long pin sets; and finally, a weather station is installed in each test hut. The sensors are distributed at three vertical levels of the wall (lower, middle, and upper) and also at three horizontal layers (interior, middle, and exterior). The monitored data is collected at 15-minute intervals and is stored in an online database in order to facilitate the offsite data access.



Figure 3: Interior sensor installation and weather station.

The American Society for Testing Materials (ASTM) recommends that the interior temperature be maintained at a constant level for the interior of the house when evaluating a given material's performance [12]. For this purpose, each house is equipped with an underfloor heating system as well as an air conditioning system, which operates only in summer. The indoor ambient condition is set to maintain a constant temperature and relative humidity of 22°C and 50%, respectively. Figure 4 presents the indoor setup for climatic conditions. Also, each test hut is paired with a weather station to monitor the

outdoor weather conditions such as temperature, solar radiation, precipitation, atmospheric pressure, and relative humidity, among others. Table 1 and Table 2 present a summary of the weather statistics of the outdoor weather conditions relevant to this study in Edmonton and Vancouver, respectively.

Table 1: Weather statistics for Edmonton

	Minimum	Maximum	Average	Standard Deviation
Temperature (°C)	-23.80	29.70	3.15	10.28
Wind Direction (°)	0.00	15.00	7.04	4.62
Wind Speed (km/hr)	0.00	66.00	6.23	5.48
Outside Rh (%)	9.00	97.00	69.23	19.91
Hourly Precipitation (mm)	0.00	5.10	0.03	0.22
Solar Radiation (Watts/m ²)	0.00	1,146.00	112.21	195.45
Dewpoint (°C)	-26.10	17.80	-2.92	7.60
Pressure (Pa)	984.00	1,035.10	1,012.75	9.02
Wind Direction (°)	5.00	360.00	216.13	99.49
Wind Speed Gust (km/h)	0.00	66.00	13.02	8.63
Daily Rain (mm)	0.00	26.20	0.28	1.63

Table 2: Weather statistics for Vancouver

	Minimum	Maximum	Average	Standard Deviation
Temperature (°C)	-23.80	29.70	3.15	10.28
Wind Direction (°)	0.00	15.00	7.04	4.62
Wind Speed (km/h)	0.00	66.00	6.23	5.48
Outside Rh (%)	9.00	97.00	69.23	19.91
Hourly Precipitation (mm)	0.00	5.10	0.03	0.22

Solar Radiation (Watts/m ²)	0.00	1,146.00	112.21	195.45
Dewpoint (°C)	-26.10	17.80	-2.92	7.60
Pressure (Pa)	984.00	1,035.10	1,012.75	9.02
Wind Direction (°)	5.00	360.00	216.13	99.49
Wind Speed Gust (km/h)	0.00	66.00	13.02	8.63
Daily Rain (mm)	0.00	26.20	0.28	1.63



Figure 4: Interior of test hut, heated floor, and temperature control.

Figure 5 presents the variation in the indoor and outdoor temperature values for Vancouver and Edmonton between December 1, 2015 and May 31, 2016.

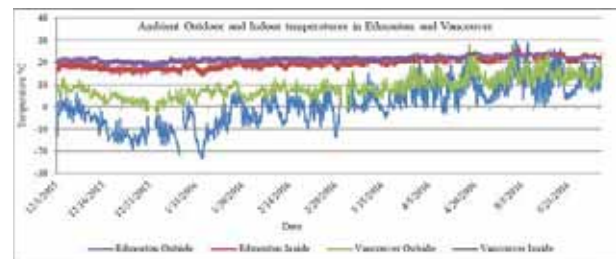


Figure 5: Indoor and outdoor temperature values for Edmonton and Vancouver (Dec. 1, 2015–May 31, 2016).

3. Method

The standard practice for determining the thermal resistance of building envelope components from the in-situ data (C1155-95/2013–ASTM) recommends two

techniques to compute thermal resistance, the summation technique and the least squares technique. For this specific project, the summation technique is selected in order to determine the thermal resistance of the wall system in terms of R-values. In this method, the difference between the surface indoor and outdoor temperature of each wall system is determined using Eq. (1).

$$\Delta T_s = T_{is} - T_{os} \quad (1)$$

where ΔT_s is the temperature difference for the surface, T_{is} is the indoor surface temperature, and T_{os} is the outdoor surface temperature.

Given that the data is collected in intervals of 15 minutes and the recommendation of the ASMT is to use that of 1-hour intervals, the data is grouped into 1-hour intervals to calculate the thermal performance using Eq. (2).

$$R_e = \frac{\sum_{k=1}^M \Delta T_{sk}}{\sum_{k=1}^M q_k} \quad (2)$$

where R_e is the estimated thermal resistance (RSI) in km^2/W ; k is the counter for summation of time series data; M is the test duration for each convergence (in hr); and q is the heat flux (W/m^2). Using Eq. (2), an estimated thermal resistance value can be calculated every hour based on the cumulative difference in temperature and heat flux for each wall.

The RSI calculations are based on 12-hour convergence intervals. The stability over time is achieved using Eq. (3).

$$\text{CR}_n = \frac{R_e(t) - R_e(t - n)}{R_e(t)} \quad (3)$$

where CR_n is the convergence factor for the chosen convergence interval.

4. Results and discussion

Two weeks of sample data are used at the time of writing this paper to demonstrate the preliminary findings of this study as illustrated in Figure 6 through Figure 13. Figure 6 and Figure 10 indicate that the interior temperature of the north-facing panels is correlated to the exterior temperature for the Edmonton and Vancouver data samples. As for the south-facing panels presented in Figure 8 and Figure 12, we observe a similar correlation but with notable peaks at the sun's peak elevation angle (i.e., at solar noon). The variance in the moisture content measurements of south-facing and north-facing

panels is presented in Figure 7 and Figure 9 for Edmonton and in Figure 11 and Figure 13 for Vancouver.

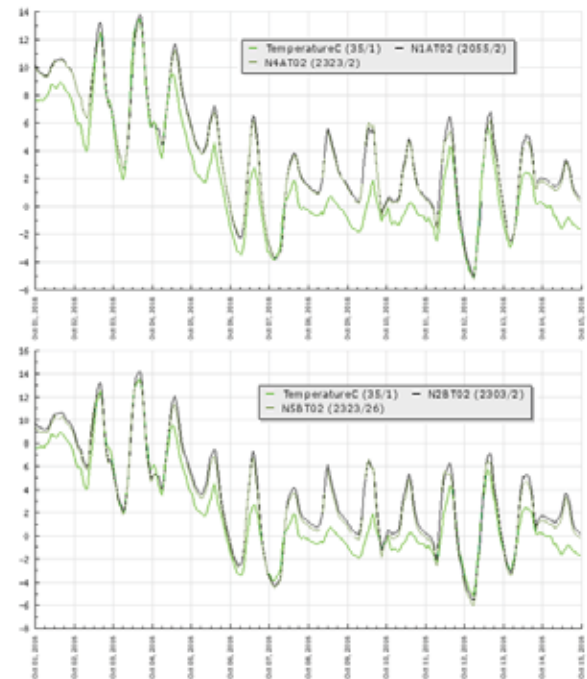


Figure 6: North-facing panels in Edmonton: type A and type B (interior and exterior temperature profiles).

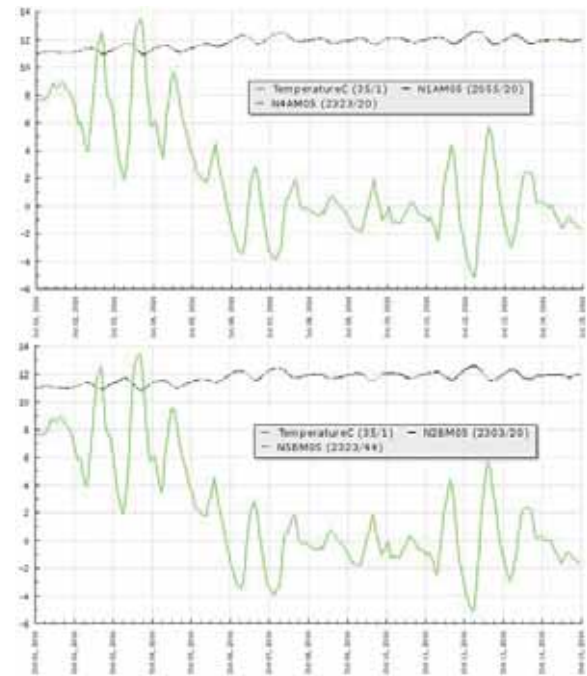


Figure 7: North-facing panels in Edmonton: moisture content in type A and type B panels.

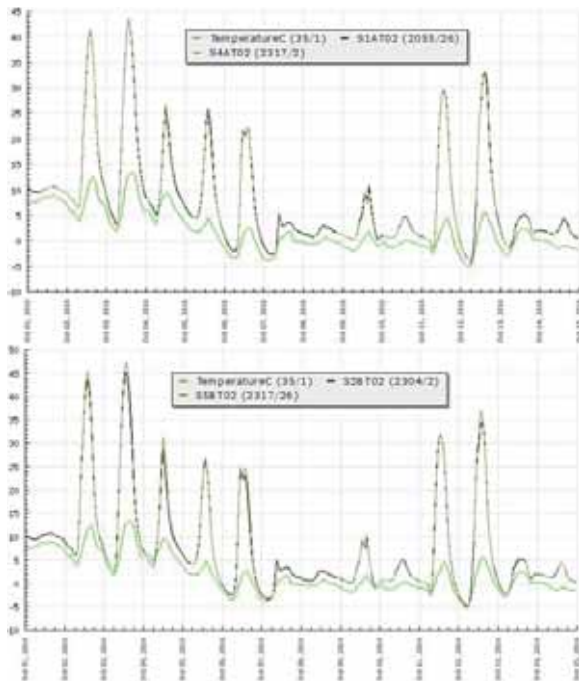


Figure 8: South-facing panels in Edmonton: type A and type B (interior and exterior temperature profiles).

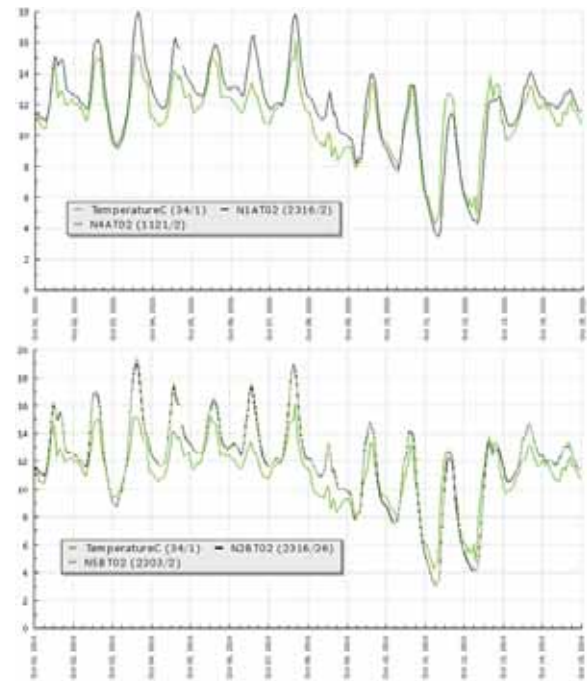


Figure 10: North-facing panels in Vancouver: type A and type B (interior and exterior temperature profiles)

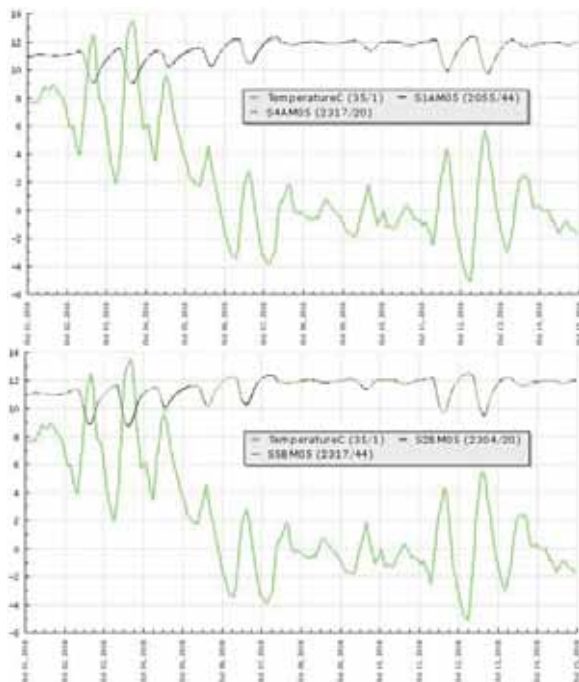


Figure 9: South-facing panels in Edmonton: moisture content in type A and type B panels.

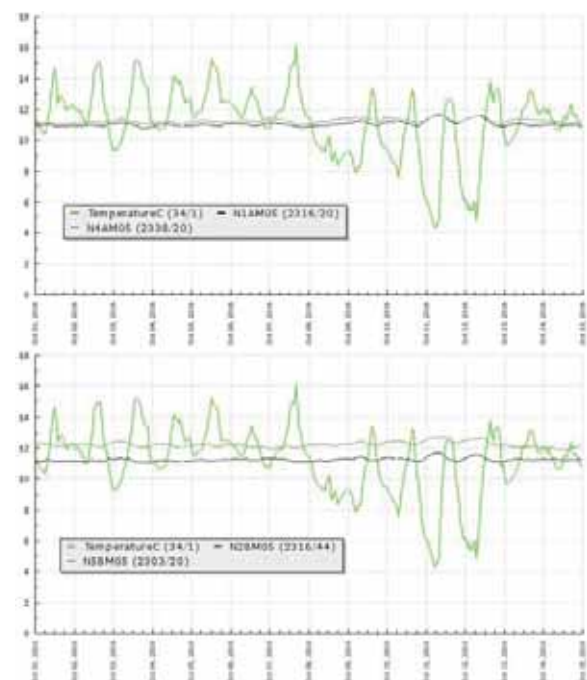


Figure 11: North-facing panels in Vancouver: moisture content in type A and type B panels.

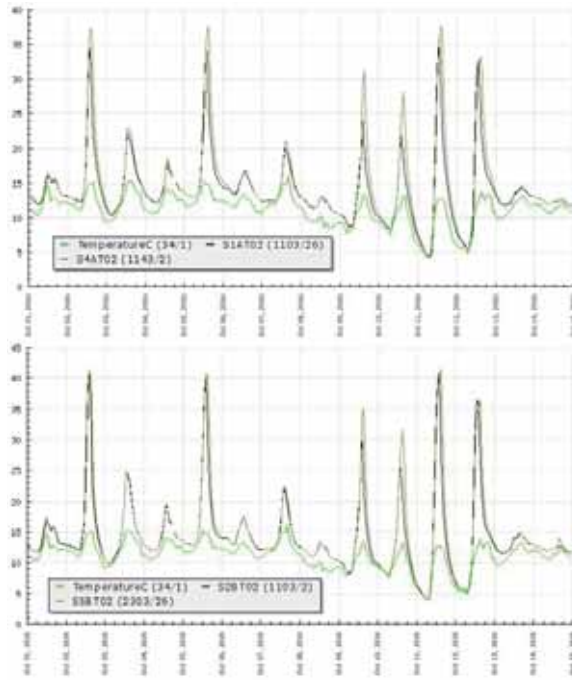


Figure 12: South-facing panels in Vancouver: type A and type B (interior and exterior temperature profiles).

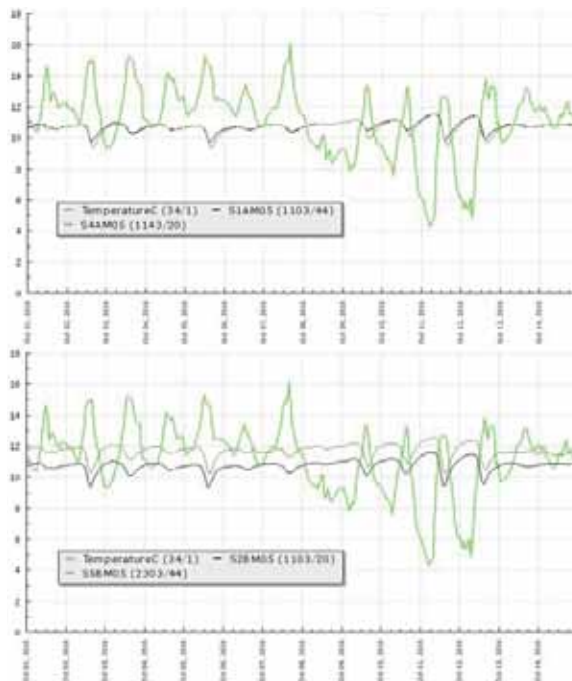


Figure 13: South-facing panels in Vancouver: moisture content in type A and type B panels.

For both sites, the highest values for moisture content are obtained at night time and the lowest values are obtained at the time of the sun's peak elevation. Also, south-facing panels reveal greater fluctuation in moisture levels than in north-facing panels.

The R-value of each of the monitored panels is calculated. Table 3 and Table 4 present a summary of the preliminary results for the R-value calculations based on the recommendations provided by ASTM.

Table 3: Preliminary results for Edmonton R-values

Panel ID	R-value			COV%		
	Stud	Cavity	MFP	Stud	Cavity	MFP
E_N1A	1.739	3.363	0.738	0.168	0.171	0.201
E_N2B	2.611	6.653	1.714	0.125	0.515	0.507
E_N3C	2.141	3.639	N/A	0.509	0.415	N/A
E_N4A	2.248	3.677	0.768	0.143	0.18	0.247
E_N5B	2.422	3.280	0.760	5.168	8.386	0.534
E_S1A	2.519	3.257	0.685	0.095	0.157	0.257
E_S2B	2.909	6.419	1.598	0.037	0.134	0.165
E_S3C	4.190	4.094	N/A	0.413	0.349	N/A
E_S4A	3.590	7.181	1.816	0.055	0.155	0.140
E_S5B	2.936	7.339	1.880	0.006	0.087	0.059

Table 4: Preliminary results for Vancouver R-Values

Panel ID	R-value			COV%		
	Stud	Cavity	Stud	Cavity	Stud	Cavity
V_N1A	2.537	7.433	1.592	0.043	0.321	0.391
V_N2B	4.747	2.887	0.723	0.437	0.754	0.728
V_N3C	2.561	3.104	N/A	0.144	0.093	N/A
V_N4A	1.290	1.116	0.245	0.294	0.346	0.316
V_N5B	2.281	3.805	0.990	0.040	0.054	0.026
V_S1A	1.456	2.275	0.516	0.255	0.274	0.124
V_S2B	1.634	2.479	0.600	0.104	0.168	0.151

V_S3C	3.885	10.419	N/A	0.735	0.628	N/A
V_S4A	3.258	4.385	0.755	0.094	0.402	0.278
V_S5B	2.384	2.592	0.622	0.090	0.180	0.122

One recommendation, according to ASTM standards, is that the coefficient of variation (COV) should be less than 10% in order to validate the R-value calculations.

However, some of the results presented in Table 3 and Table 4 do not meet this criterion. The cause of this un-met criterion results from data gaps due to cleaning and possible malfunctioning of some sensors. As the data collection process has been ongoing since 2015, more comprehensive and accurate results are expected to be published in the near future.

In general, the R-values for south-oriented panels are found to be higher than those of the corresponding north-oriented panels.

5. Conclusions and outlook

In this paper, the experimental setup for evaluating the hygrothermal performance of two multi-functional panels (MFPs) is discussed and various hygrothermal parameters are measured. Preliminary R-values are calculated.

The next step of this ongoing project is to conduct data cleaning and processing to obtain the long-term R-values. Also, investigation of moisture conductivity of the panels will be carried out and characteristics of the MPFs, such as density, conductivity, and thermal mass, will be analyzed.

Additionally, the data provided by the weather station will be used to analyze the impact of wind speed, precipitation, solar radiation, and atmospheric pressure on the MFPs' hygrothermal performance.

This experimental setup has been installed to investigate and analyze the hygrothermal performance of the abovementioned MFPs. This is an ongoing project, and future studies will discuss the project results and findings in detail.

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Crystalline Waterproofing Admixtures Effects on Self-healing and Permeability of Concrete

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Abstract:

This paper investigates the effect of adding crystalline admixtures (CA) on the self-healing and permeability characteristics of concrete. Also, the effect of these admixtures on modifying the concrete microstructure is demonstrated. The depth of water penetration per DIN 1048 and the rapid chloride permeability (RCP) test per ASTM C1202 were conducted on concrete mixes with CAs. The CA addition had a significant effect on the water penetration depth and permeability characteristics of concrete. In regard to the microstructure, the growth of pore-locking crystals was observed using Scanning Electron Microscopy (SEM) while these crystals were examined using Energy Dispersive X-ray (EDX) analysis to not be ettringite. In addition, the permeability coefficient (k_w) of water penetrating in unsaturated concrete under hydrostatic pressure per DIN 1048 was estimated based on the average depth rather than the maximum depth of penetration. It was found that the electrical charge passed in Coulombs reduced for treated samples during RCP test when compared to reference samples as temperature increases. Using an innovative and straightforward technique developed by authors, the higher reduction in flow through cracked specimens was also observed for CA treated concrete, indicating better self-healing efficiency of these mixtures. This paper also reviews the previous works that have been done on crystalline admixtures.

Keywords:

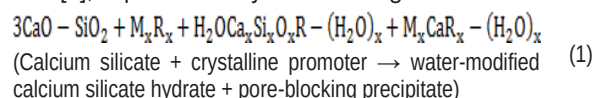
Self-healing, crystalline admixtures, water permeability, rapid chloride permeability, microstructure

1. Introduction

Chemical admixtures are predominantly water-soluble ingredients used to improve concrete's construction properties in the fresh state, its mechanical properties in the hardened state, or both [1]; consequently, they lead to sustainable development and increase in service life of concrete structures. Typically, their effects on concrete properties in the plastic stage include increased workability, improved pumpability, setting time, or finishability; on the other hand, when concrete hardens, chemical admixtures contribute in improving durability, increasing compressive and flexural strength at all ages, reducing shrinkage phenomena, or decreasing permeability of concrete. Chemical admixtures also act as agents which allow the manufacture and construction of special concrete types such as self-healing concrete, high-strength concrete, self-consolidating concrete [2]. Among these special concrete types, Engineered Self-healing Concrete (EShC) is a type of concrete which has a capability to autonomously heal cracks inside its matrix to a certain level, by incorporating various substances such as crystalline products; thus, increases its service-life. It should be noted that concrete inherently can heal its cracks. This autogenous healing phenomenon results from the chemical and/or physical composition of cementitious matrix and is only effective for small crack widths up to 200 μm [3]. Due to small crack width closure, autogenous healing is not a reliable phenomenon to achieve noticeable healing effects. Hence, in recent years, more attention has been paid to EShC which is

associated with artificially triggered healing mechanisms into the cementitious matrix and presented mainly by some chemical or biological agents such as the use of microencapsulated healing agents, bacterial concrete, or the use of crystalline admixtures.

Among those aforementioned proprietary chemical admixtures, Crystalline Admixtures (CA) are one of the Permeability-Reducing Admixtures (PRAs) types as described by the American Concrete Institute (ACI) Committee 212 [1]. Contrary to hydrophobic or water-repellent materials, these products are hydrophilic which makes them react easily when moisture enters the pores/cracks of concrete. After taking this reaction in place, CA forms water insoluble pores/cracks blocking crystals which improves the healing efficiency of concrete. Also, CA increases in density of Calcium Silicate Hydrate (C-S-H, main cement hydration product) and thus, makes concrete more resistant to penetration of aggressive ions. Depending on the crystalline promoter and the precipitate formed from calcium and water molecules, active chemicals contained in cement and sand form these products. As a result of crystalline depositions into concrete matrix, water pressure resistance of modified matrix increases as high as 14 bars [1]. An overview of the general process, as reported by the ACI Committee 212 [1], is presented by the following:



Crystalline-based technology has been used over the past two decades in the construction industry and its effectiveness on reducing concrete permeability is well-understood; however, only limited research work has been done to analyze the effects of these admixtures in order to enhance the SH mechanisms and long-term durability.

Awni Al-Otoom *et al.* [4] experimentally investigated a new water-based crystallization technology to reduce permeability of concrete. This technology is dependent on the formation of sodium acetate crystals inside the pores of concrete. It was reported that an optimum solution of 20 wt % sodium acetate delivers the best minimization of water penetration into concrete without altering the physical and performance properties of the concrete. However, the treatment solution only penetrated 0.5 inch while it is expected to grow even deeper than that. The visual closure of crack produced by various additives in mortar specimens comparing with a reference Portland mortar using fly ash, expansive admixtures, silica fume, CA and limestone powder under water immersion condition were also studied by Jaroenratanapirom and Sahamitmongkol [5], [6]. They reported that CAs improved the SH process for cracks with less than 0.05 mm width at higher rate than the other additives types; however, they became inefficient for wider cracks.

SH potential of cement-based materials incorporating Calcium Sulfo-Aluminate (CSA) based expansive additive and CA has been investigated in Sisomphon *et al.* study [7]. The effects of both CSA and CA on surface crack closing ability, water tightness and microstructures of pre-cracked mortar specimens were also studied. In their experimental setup, a surface crack width of between 100 and 400 μm were induced into specimens at age of 28 days which already were reinforced with galvanized wire-mesh at the mid-height to obtain desired crack width. As an indicator of quantitative evaluation of SH, the change of surface crack width was considered. Within 28 days' test period, for control mixes and CA/CSA addition samples, it was found that surface crack up to about 150 μm width and up to 250-400 μm have been completely closed. However, using concrete instead of mortar and larger specimen size which give a better simulation of real-world condition have not been considered in this study. Ferrara *et al.* [8] studied the effects of CA on the SH of concrete and their healing capability on the recovery of mechanical properties; evaluated the influences of the SH phenomena on the recovery of stiffness and load-bearing capacity by means of 3-point bending (3pb) test before and after conditioning [8]. In addition to that, Ultrasonic Pulse Velocity (UPV) tests and microstructural observations have been performed. For water immersion condition, it was reported that the presence of CA sped up the crack healing process and recovered the bending stiffness and load-bearing capacity of concrete. In the case of air exposure, CA

treated concrete showed highly effective in engineering the SH and recovery of material mechanical properties, while no significant recovery neither of material continuity nor of its mechanical behavior was observed in the absence of CAs. It was also found that a crack closure above 70-80% is necessary to start recovery of stiffness and load bearing capacity [8]. Similarly, under four different exposure conditions (wet/dry cycles, humidity chamber, water immersion with/without renovation, and air exposure), the healing effect of CA in terms of strength recovery were studied in [9]. In contrast to previous study, CA showed a better SH capacity under wet/dry exposure.

Using a different technique, a similar study by Roig-Flores *et al.* [10] investigated the effects of CAs only on the SH of concrete in four various types of environmental exposure conditions. Based on the measure of the global permeability of the specimen and different geometrical characteristics of the crack before and after the SH period, they developed a method that can evaluate the SH properties of cracked samples. It was stated that neither control specimens nor those with CA healed when exposed to moist conditions. In their findings, the four exposures in order of decreasing permeability healing ratio were: WI (around 0.9) > WC (around 0.8) > HC (around 0.5) > AE (around -0.15) [10]. Following to previous study, Roig-Flores *et al.* [11] work analyzed the SH properties of early-age concretes, engineered using CA, by measuring the permeability of cracked samples and their crack width. Under three different exposure conditions, they considered the SH behavior in two typically used concrete classes, one common for precast concrete elements (C45/55) and one standard class broadly used for building constructions (C30/37) [11]. Under water at 15 °C and especially at 30 °C, it was concluded that healing ratio was higher for CA treated specimens compared to those for control; however, the high-scattered results were observed for both treated and un-treated concrete under the wet/dry cycles exposure. The obtained results were slightly better when using CA in the high-performance concrete, mainly due to the lower scattering of results. In recent study by Ferrara *et al.* [12], the influences of crystalline admixtures on the self-healing capacity of the cementitious composites with reference to both a Normal Strength Concrete (NSC) and a High Performance Fiber Reinforced Cementitious Composite (HPFRCC) have been evaluated. Both in the case of NSC and HPFRCC, the CA enhances and makes more reliable the autogenous healing capacity of cementitious composites. In NSC, CAs could promote up to 60% of crack sealing even under exposure to open air. In the case of HPFRCCs, which would already feature autogenous healing capacity because of their peculiar mix compositions, the synergy between the dispersed fibre reinforcement and the action of the CAs has resulted in a likely 'chemical pre-stressing' of the same reinforcement, from which the recovery of

mechanical performance of the material has greatly benefited, up to levels even higher than the performance of the virgin un-cracked material.

In this paper, the microstructure characterised by Scanning Electron Microscopy (SEM), the water permeability coefficient per the DIN 1048 test, the electrical charge in Coulombs per the ASTM C1202 RCP test, and self-healing efficiency using an innovative technique developed by authors were determined for concrete treated with crystalline waterproofing admixtures.

2. Experimental Program

2.1 Materials and specimen preparation

In accordance with ASTM C150, Ordinary Portland Cement (OPC)- Type I (also referred as type GU in CSA A23.1-14 [13] was used for all batches. The concrete compositions of this cement type were further modified by adding crystalline admixtures (CA), in powder form, at a dosage equal to 2% by the weight of cement, called OPC_CA in this study; its behavior is being compared with control specimens (without CA). A special category of hydrophilic permeability reducing admixtures (PRAs) commercially produced was used as CA. However, the chemistry of this product is proprietary and available. For each mixture, cylinders of $\Phi 100$ mm $\times$ 200 mm, $\Phi 100$ mm $\times$ 150 mm, and $\Phi 150$ mm $\times$ 175

mm were prepared with a constant water/cement (w/c) ratio of 0.532 in accordance to recommendations by ASTM C192 [14] practice. This water/cement ratio is typical for concrete exposed to severe rain or alternate wetting and drying; concrete entirely immersed in sea water or exposed to coastal environment. In accordance with ASTM C143 [15], slump flow test were performed within 15 minutes after preparing the mixes to avoid any loss of workability with time. For all mixtures, air content was also determined by following procedure in ASTM C231 [16]. The density of a fresh concrete batch is measured in accordance with ASTM C138 and it is theoretically defined as the mass to volume ratio [17]. For measuring fresh mixture density, a container of known volume and weight is filled to the brim with the freshly prepared concrete mixture. The fresh mixture was rodded to compensate the possibility of excessive loss in entrained air [17]. Temperature of fresh concrete mixture was measured in accordance with ASTM C1064 [18]. A thermometer was placed in different location of the mixture after the mixing process is complete and average reading of the temperature is reported. After 28 days of curing, compressive strength tests on three cylindrical specimens were conducted on all the mixes in accordance to ASTM C39 [19]. Table 1 represents the masses of materials used per m³ and fresh/hardened concrete properties for each mixture.

Table 1: Mix proportions and fresh/hardened concrete properties

Mix ID	Mix proportions (kg/m ³)				w/c	Fresh properties				f _c
					ratio					(MPa)
	Cement	Aggregates		Water	CA (2%)	Slump (mm)	Air content (%)	Plastic density (kg/m ³)	Temp. (°C)	
		Coarse (5-14mm)	Fine							
OPC					×	130	2.0	2400	21.0	34.6
OPC_CA	358	990	862	190	7.16	110	2.2	2394	21.0	36.2

2.2 Items of investigation

2.2.1 Microstructure

The objective of this experimental phase is to investigate the effects of CA on modifying the cementitious materials' microstructure and if the pore-blocking crystals can be identified and photographed using Hitachi S-4800 Scanning Electron Microscope (SEM). To satisfy the objective, ordinary Portland cement, sand, and water, with an addition of CA in some cases, were mixed manually together to prepare mortar cubic specimens (50×50×50 mm). After casting, cubes were plastic wrapped for a period of 24 hrs and later, cured in the water tank. After 56 days of immersion in the water, specimens were broken into the small pieces with fresh fracture

surface for further investigations on SEM. The specimens were left in the ambient temperature for 7 days to dry. Next, surface of three samples from each mix were coated with carbon to dissipate excess charge from the specimen.

2.2.2 Water permeability coefficient

In this phase, the water permeability of mixtures described in Table 1 is studied using DIN-1048-Part 5 test. In accordance with DIN standards, three specimens from each mixture were subjected to 0.5 MPa (5 bar) of hydrostatic pressure for 72hrs. Each specimen was mounted into a cell consisting of a rubber gasket with a 100-mm diameter to avoid leakage while applying water pressure. After the testing was completed, the samples were split in half

using a compression machine and the depth of penetration in each sample was measured. Coefficient of water permeability (k_w) can be determined using measured water depth according to modified Darcy's Law [20] as follows:

$$\frac{dx}{dt} = k_w \frac{h}{x} \quad (2)$$

where x is the penetration depth (m), t represents the experiment time (s), k_w indicates the permeability coefficient (m/s), and h is the water head (m). Permeability coefficient can be simply derived by integrating Eq. (2) to obtain Eq. (3):

$$k_w = \frac{x_t^2}{2ht} \quad (3)$$

where x_t is the penetration depth at time t . Since the water flow is unsteady and associated with sorptivity, it is more reasonable to consider average depth of water penetration instead of maximum one to calculate k_w . Using AutoCAD software, the x_{avg} for divided specimens was determined by measuring the wetted area (A_w) and maximum width (W_{max}) of this region as shown in Figure 1. Then, x_{avg} was calculated as the average of the A_w divided by W_{max} for each half.

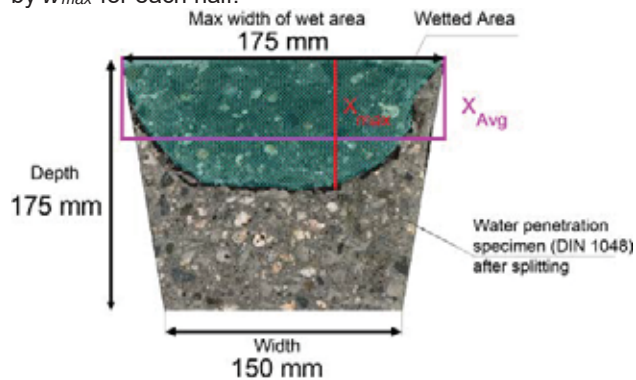


Figure 1. Method for calculating the average depth (x_{avg}) in the wetted region.

2.2.3 Rapid Chloride Permeability (RCP) test

Following procedure reported in ASTM C1202 [21], the RCP test was performed on concrete slices with 50-mm thickness, cut from four $\Phi 100$ mm $\times$ 200 mm cylinders. To ensure one-directional Cl^- ions penetration, the side surfaces around the circumference of concrete slices were epoxy-coated. Afterward, the disks were vacuums saturated (for 3 hours period), deaerated, and then submerged in water for 18 ± 2 hrs before testing (Figure 2-a). Specimens were then mounted into test cells of Giatec Perma2™ device containing of two reservoirs, where one reservoir was filled with 0.3 N NaOH solution (anode), and the other with 3% NaCl solution (cathode), shown in Figure 2-(b). 60 V potential difference was applied during test to allow the transfer of chloride ions through concrete from cathode (NaCl solution) to anode (NaOH solution). The test was conducted for a six-hour period, during which the current and the temperature were measured every minute. The total charge passing was measured in

Coulombs and the average value of four samples was reported.

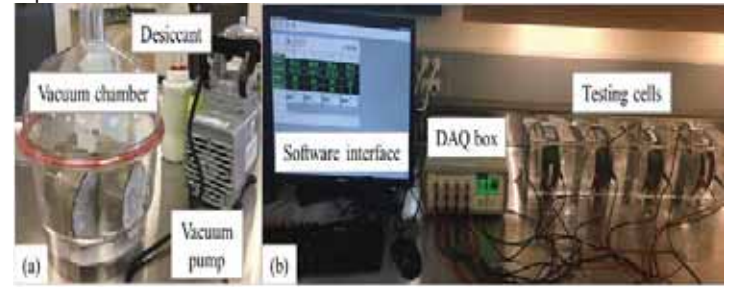


Figure 2. (a) water saturation setup (b) RCP test apparatus.

2.2.4 Self-healing test

During this experimental phase, three CA treated specimens and control concrete mixtures were prepared and later cracked according to innovative technique reported in [22] to examine self-healing capability of cracked cylinders. One of the major consideration in this test method, is to use simple and readily available specimens that are commonly prepared for determining compressive strength of concrete. All cylinders were cured for 48 hrs in ambient conditions. After 2 days of curing, each sample was placed in a Standard Crack-Inducing Jig (SCIJ) to induce a crack width ranging from 0.1 to 0.3 mm using MTS Universal Testing Machine. A load range of 1.15 kN/s – 2.5 kN/s was used to induce cracks. Surface crack width for each cylinder (top and bottom sides) was measured by an optical crack-detection microscope at 14 equidistant points along the crack: seven along the top face, and seven along the bottom face. The measurements were averaged and recorded as the cylinder average. The cracked specimens were later inserted in special rubber sleeves and then one end of cylinder sample was exposed to a constant water head (usually 1-2m). The flow of water through specimens was collected in water containers and measured over a period of time. It should be noted that depending on the water head chosen for the test and the width of the crack, the initial flow through the specimens could be large. This may need fairly large size containers and it may require frequent readings and emptying the containers frequently. Details of the self-healing test is shown in Figure 3.

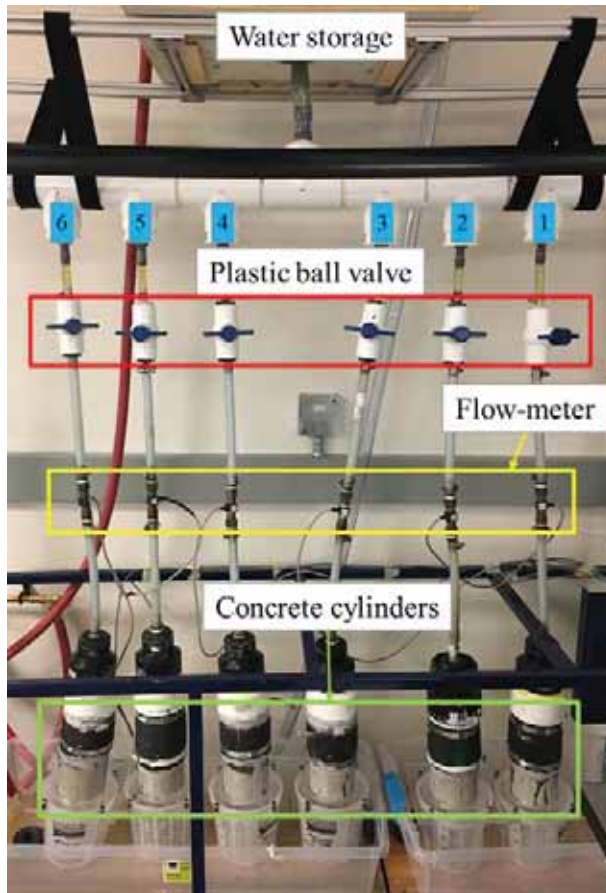


Figure 3. self-healing apparatus.

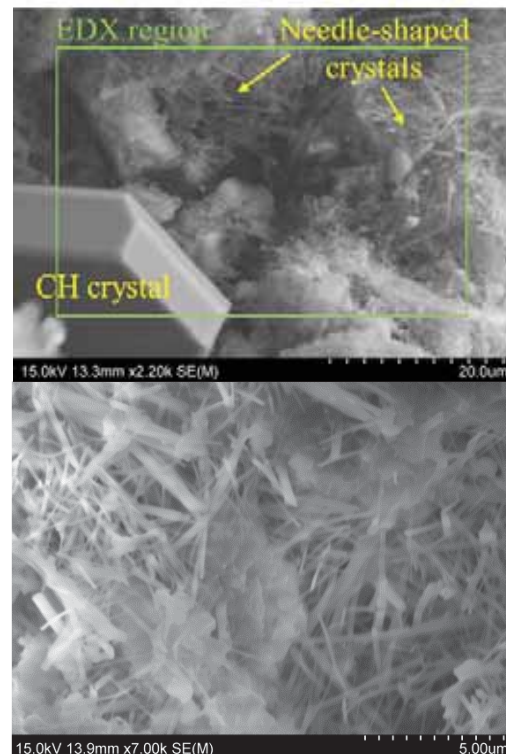
3. Results and discussions

This section is aimed to demonstrate the effect of crystalline admixtures on the microstructure, the electrical charge passed based on RCP test, the depth of water penetration based on the DIN 1048, the self-healing, and the crack closure.

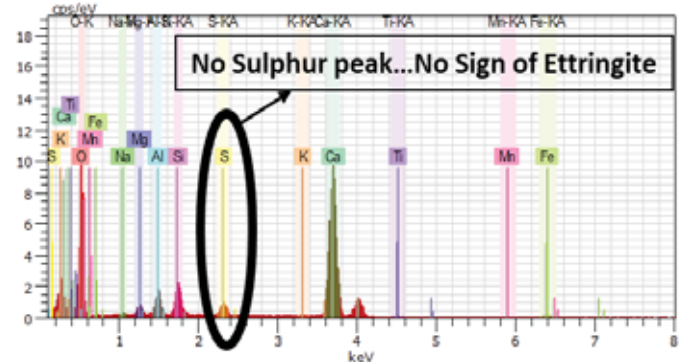
3.1 Microstructure

SEM analyses were carried out on fragments collected from mortar specimens to observe and identify the needle-like crystals. SEM observations of both CA treated, and control samples are shown in Figure 4 & Figure 5. Figure 4 exhibits the needle-like crystals growing in CA treated samples and blocking cracks/voids while in the control specimens, the cracks/voids were left uncovered. These images are good indicators of crystalline admixtures performance in closing voids and cracks. These crystals are up to 3-8 μm in length and some of them are less needle-like perhaps signifying either different composition or greater development. It should be mentioned that ettringite crystals are also known for having a “needle-like” (i.e. acicular) shape. The chemical formula for ettringite is $3\text{CaO}\cdot\text{Al}_2\text{O}_3\cdot3\text{CaSO}_4\cdot32(\text{H}_2\text{O})$, and is 19.16% Ca, 4.3% Al, 7.66% S and 63% O in atomic percent. To differentiate between the discovered crystals in the KIM specimens and ettringite, the

specimens were considered for further analyses using EDX. The results of EDX analysis show that the matrix of CA treated specimens is relatively homogenous in chemical compositions. Also, from initial analysis, it appears that the composition of the “needle-like” crystals in the CA specimens are different from the ettringite due to low peak of sulphur (S) in the EDX graph which is one of the major elements in the ettringite chemical composition.



(a)



(b)

Figure 4. CA treated mortar (a) SEM micrograph (b) EDX spectrum.

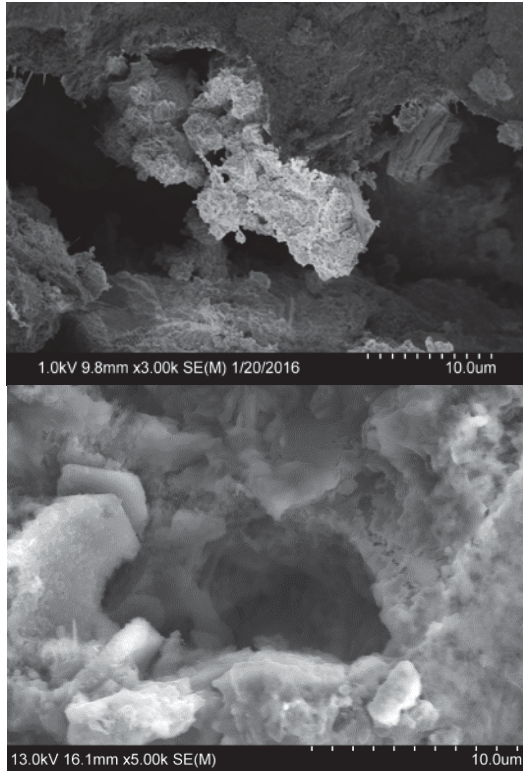


Figure 5. SEM micrograph of control mortar.

3.2 Water Permeability Coefficient

The maximum and average depth of water penetration (x_{max}) for CA treated (OPC_CA) and control (OPC) specimens are based on the DIN 1048 test as summarized in Table 2. As expected, the penetration depth reduced for mixtures containing crystalline admixtures, proves their capability to make concrete waterproof. Hedegaard and Hansen [23] stated that concrete is considered as watertight for all practical purposes when the x_{max} is less than 50 mm. Readings of OPC_CA samples indicated less than 50 mm maximum penetration depth. The relation between the average and maximum penetration depth for OPC_CA and OPC specimens is shown in Figure 6. The figure reveals that there is a trend between the x_{max} and x_{avg} . This trend is observed to be linear with an acceptable correlation coefficient of 0.99 for OPC samples ($R^2=0.99$) and relatively poor correlation coefficient of 0.23 for OPC_CA samples ($R^2=0.23$). From the tested DIN 1048 specimens, it was also observed that for larger water penetration depths, the flow can either become more evenly spread along the exposed surface or more oriented towards a specific location. Both average and maximum penetration depth were later used to predict the water permeability coefficient of concrete (k_w) from Eq. (3) as presented in Table 2. In both mixes, similar trend between average and maximum coefficient of water permeability was observed (Figure 7). Since measurement of the average depth (x_{avg}) indicates better predication of k_w when compared to maximum depth (x_{max}), the relationship between the x_{avg} and

$k_w(avg)$ for OPC and OPC_CA samples is shown in Figure 8. While a quadratic trend was observed with a strong correlation coefficient ($R^2=0.99$) for all mixtures, OPC samples indicated higher standard deviation than OPC_CA ones.

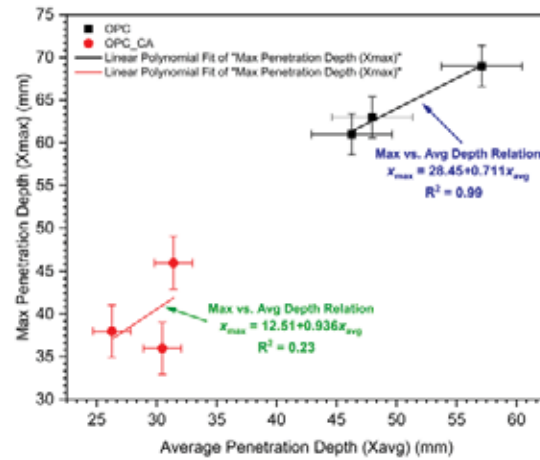


Figure 6. Maximum versus average penetration depth per DIN 1048.

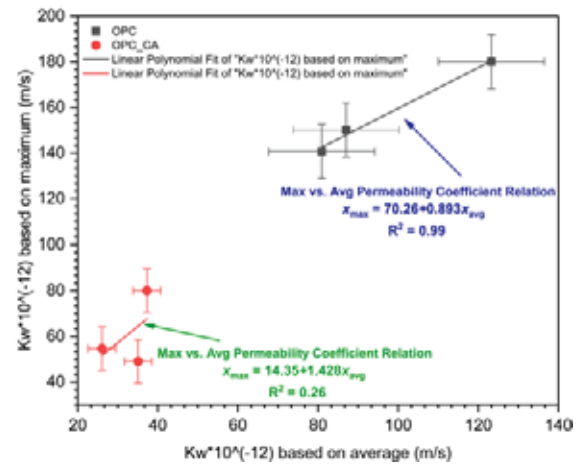


Figure 7. Maximum versus average water permeability coefficient per DIN 1048.

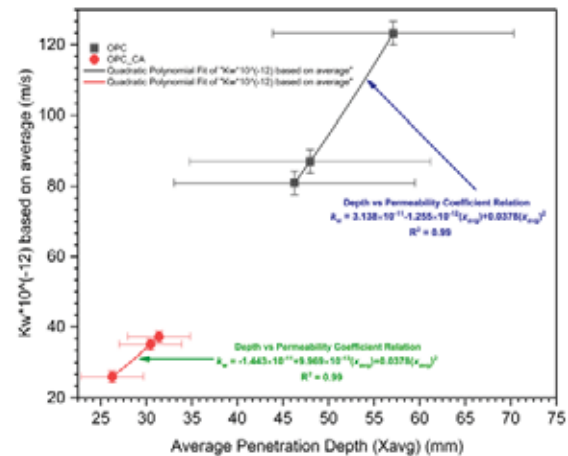


Figure 8. Relation between average penetration depth and water permeability coefficient.

Table 2: Water permeability test results

Sample ID	Max penetration depth $\times 10^{-3}$ m ($X_{\max}$)	Average penetration depth $\times 10^{-3}$ m (X_{avg})	Based on $X_{\max}$		Based on X_{avg}	
			Permeability coefficient $k_{w(\max)} \times 10^{-12}$ m/s	Average $k_{w(\max)} \times 10^{-12}$ m/s	Permeability coefficient $k_{w(\text{avg})} \times 10^{-12}$ m/s	Average $k_{w(\text{avg})} \times 10^{-12}$ m/s
OPC I	63	48	150.1		87	
OPC II	61	46.3	140.7	156.9	80.9	97.1
OPC III	69	57.1	180		123.3	
OPC_CA I	38	26.3	54.6		26.1	
OPC_CA II	36	30.5	49	61.2	35.1	32.8
OPC_CA III	46	31.4	80		37.3	

3.3 RCP test

The current in mA for all the concrete specimens, measured for 6 h, is based on the RCP tests at 28 days; shown in Figure 9. Higher variations were experienced with OPC_CA I and OPC_CA II samples. The current for OPC_CA samples gave slightly lower results than OPC ones, indicating better performance of treated specimens. The cumulative electrical charge in Coulombs, which geometrically indicates the enclosed area of the curve and coordinate axes, was obtained by integrating the current values with respect to time. The total charge passed in Coulombs for all concrete samples are summarized in Table 3. It was found that all OPC samples had higher electrical charge with lower standard deviation than CA treated samples. The average electrical charge of OPC_CA mix is 4399.3 Coulombs, which according to ASTM C1202 standard can be classified as having “high” chloride ion penetrability at 28 days age of curing. Similarly, the charge passed of OPC mix was determined to be 5538 Coulombs, which is the same class as OPC_CA one. High chloride ion penetration values were expected as relatively high w/c ratio was

chosen. Overall, concrete samples treated with crystalline admixtures indicated fairly reduction in electrical current; thus, lower chloride penetration than control samples.

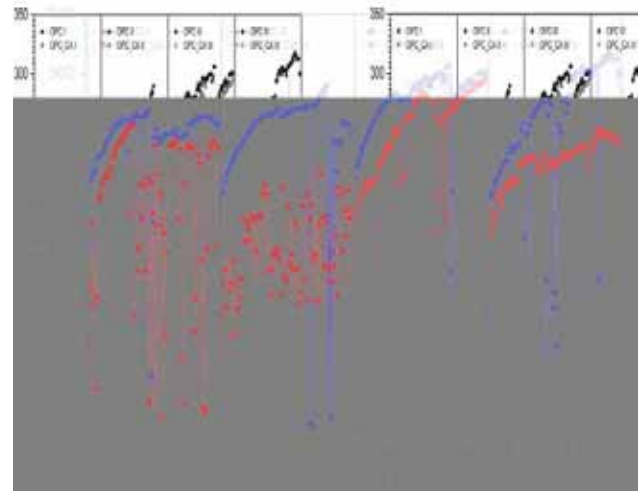


Figure 9. RCP test: current versus time per ASTM C1202.

Table 3: Rapid chloride permeability test results

Sample ID	Channel #	Electrical charge, Q (Coulomb)	Average Q (Coulomb)	Relative standard deviation (%)	Temperature difference (°C)
OPC	I	5365	5538	6.04%	28
	II	5235			
	III	6000			
	IV	5552			

OPC_CA	I	4100	4399.25	21.09%	25
	II	3261			
	III	5405			
	IV	4831			

3.4 Correlation between water permeability and RCP test

To provide a better insight on the advantages of using X_{avg} for k_w coefficient calculation, the X_{avg} and X_{max} from DIN 1048 test results were correlated with the electrical charge passed (Q) obtained from the RCP test results for treated and un-treated samples. Water permeability coefficient (k_w) based on average and maximum penetration depth values were also correlated with charge passed. The results are exhibited in Figure 10 and they revealed that there exists a quadratic trend between the water penetration depth and the electrical charge. The correlation of charge passed with the X_{max} appeared to be more consistent, less scattering and better correlation for both mixtures. It should be noted this is not an indication of whether the water penetration values are more reliable than RCP test results.

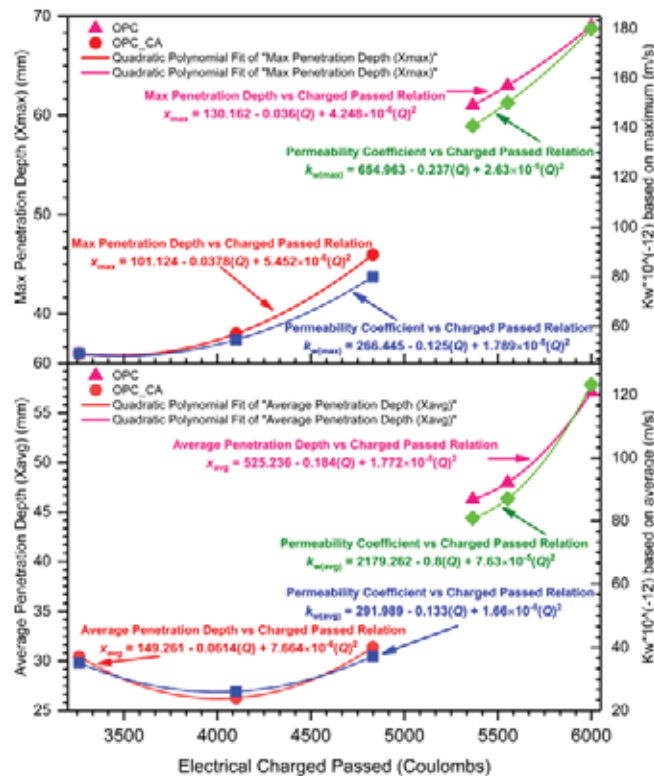


Figure 10. Penetration depth and permeability coefficient per DIN 1048 versus charge passed per RCP test

3.5 Self-healing and crack closure

The average surface crack width in mm and flow data measured for two mixtures is presented in Figure 11. The specimens experienced a rapid initial flow during the first day of exposure to water pressure; however, the flow reached to constant rate within days. As expected, the higher the crack width, the higher the initial flow. The OPC_CA samples had an average measured crack width of 0.245 mm as compared to 0.244 mm for OPC samples, which resulted in similar initial flow for both mixtures. It can be observed that the flow through the specimens reduced over time indicating "self-healing" of concrete. From this data, the time required for flow to reduce to a certain threshold value can be determined or the time required for completing sealing of cracks can also be found. The addition of the crystalline admixture yielded positive results with regards to self-healing. The surface crack width and measured initial flow are summarized in Table 4. The calculated flow reduction in OPC_CA samples was higher than OPC samples. From the analyzed data in Table 4, it is clear that the samples being compared had similar equivalent crack widths. If the calculated crack widths for specimens are not similar, then either these specimens should not be compared, or a note of dissimilar crack widths should be mentioned.

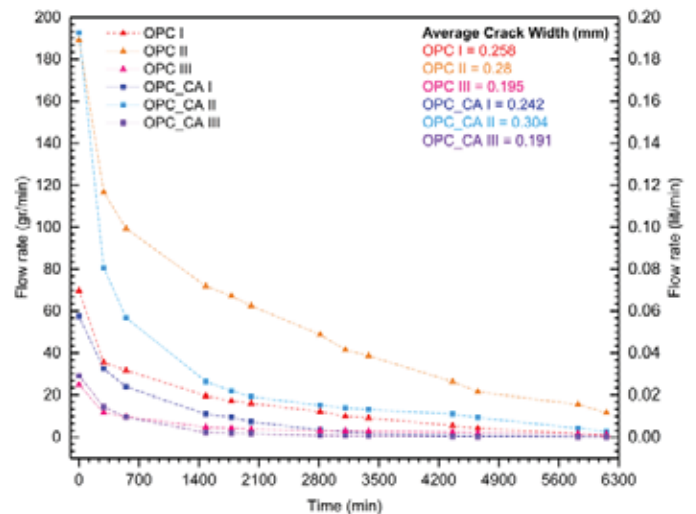


Figure 11. Measured flow rate against time

Table 4: Measured crack width and initial flow

Sample ID	Surface crack width (mm)			Real initial flow q_r (liter/min)	Percent flow-reduction rate $q_{(t)}/q_0$
	Top	Bottom	Average		
OPC	I	0.226	0.290	0.0696	99.1%
	II	0.292	0.268	0.1891	93.8%
	III	0.184	0.206	0.0248	94.1%
OPC_CA	I	0.230	0.254	0.0575	99.6%
	II	0.332	0.275	0.1926	98.5%
	III	0.176	0.205	0.0290	99.7%

4. Conclusions and outlook

Based on the findings in this study the following conclusions can be made:

- SEM images exhibited that needle-shaped crystals grew inside the crystalline admixtures treated samples while untreated concrete samples were uncovered with these pore-blocking crystals.
- The water penetration test results showed that incorporation of crystalline admixtures led to decrease in water penetration depth; thus, in water permeability coefficient.
- The average depth of water penetration appeared to provide a reasonable measure for the water penetration coefficient prediction when compared with the maximum depth of water penetration.
- The electrical charge passed in Coulombs results according to ASTM C1202 test indicated that concrete treated with crystalline admixtures resulted in lower chloride ions penetration.
- Self-healing test results presented in this study showed that crystalline water proofing admixtures can be effective in reducing the required time to self-seal cracks in concrete.
- Further investigation is required to validate the effectiveness of crystalline admixtures and accuracy of the water permeability coefficient, chloride ion penetration based on the ASTM C1202 test, and the relationship between them. This can be carried out by conducting wider range of testing that includes different cementitious combinations and contents, w/cm ratios, curing conditions, and the inclusion of larger samples geometry.

Acknowledgements

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Exploring the Factors Affecting Home Energy Retrofit Adoption – A Case Study of the EcoENERGY Retrofit Program

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Abstract:

In the wake of the global financial crisis, the Canadian government created the EcoENERGY Retrofit for Homes program with the stated goal of “Encouraging homes to become more energy-efficient, reduce emissions produced through energy use, and contribute to clean air, water, energy, and a healthy environment for Canadians.” However, results varied considerably nationwide. An early review of this data suggests that retrofits were not adopted with spatial or temporal uniformity.

Population data on were obtained from the 2006 and 2011 censuses and the National Household Survey; these were then matched with household pre- and post-retrofit data from the EcoENERGY Retrofit program. Multiple linear regression analysis of the retrofit adoption rate was conducted at the finest spatial resolution common to these datasets.

This preliminary analysis suggests that income, non-condominium properties, and high shelter costs (greater than 30% of household income) had a significant positive correlation with adoption of retrofit measures at a 99.9% confidence level. Meanwhile, renter-occupied units and participation in the workforce were negatively correlated. Seasonal variation was also observed, with the majority of retrofits occurring in winter months. Further, spatial variation at both the city and neighbourhood level suggests a greater degree of program customisation is required to ensure uniform building stock improvement.

The findings fit with an emerging pattern that grant programs can be effective at delivering high volumes of savings but have a limited market impact in the post-funding period; ~25% of energy advisors were laid off after the conclusion of the initial program end date of March 2011, tied to a sharp decline in the number of energy audits. This study reinforces the importance of the upfront cost barrier and consistent federal-level support. However, retrofit program design may need to provide different grants in different municipalities to address specific community needs.

Keywords:

Residential retrofit; energy efficiency; technology adoption; spatial/temporal considerations; retrofit grants

1. Introduction

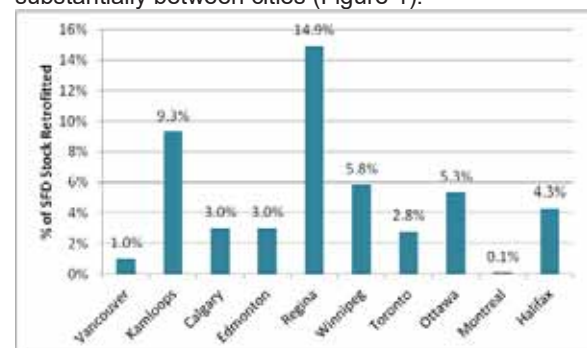
In the wake of the global financial crisis, the Canadian government created the EcoENERGY Retrofit for Homes with the stated goal of: “Encouraging homes to become more energy-efficient, reduce emissions produced through energy use, and contribute to clean air, water, energy, and a healthy environment for Canadians.”

The EcoENERGY program summary ran nationwide 2007-2012 in two stages (first stage concluded in March 2011). It offered over Can\$1B in grants, up to Can\$ 5,000 per household, for efficient heating appliances, insulation, windows, doors, air sealing, HVAC systems, and hot water heaters. The program required both pre- and post-retrofit audits in order to be eligible for a grant.

Energy advisors carried out home energy audits for over 600,000 single-family dwellings (SFD) or 7% of the Canadian stock, stimulating over Can\$10B in economic activity.^{1,2,3} Modelled estimates of energy

performance of retrofitted homes suggest demand reductions of 20%, on average.³

However, results varied considerably nationwide. An early review of this data suggests that retrofits were not adopted with spatial or temporal uniformity. For example, the share of the existing single-family dwelling (SFD) stock that adopted retrofits differ substantially between cities (Figure 1).



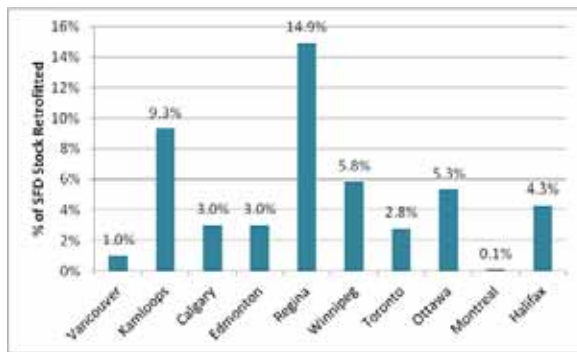


Figure 1: Percentage of SFD Stock Retrofitted during the ERfH Program

This study presents early results of spatially and temporally disaggregated information on retrofit adoption across Canada. This can be used to inform future retrofit programs, which are now being considered in a number of Canadian jurisdiction

2. Methods

In order for households to be eligible for EcoENERGY grants, pre- and post-retrofit audits were required. These audits were conducted by certified energy advisors who used energy demand modelling software (HOT2000) to determine the baseline and post-retrofit annual energy consumption. The modelling software considered house characteristics such as floor area, volume, local climate, in addition to energy-related installations. Location data (forward sortation areas, FSAs) were also provided by auditors.

The percentage of homes that completed a retrofit after the audit is termed the conversion rate, and serves as an indicator of the programs' ability to convert initial interest into energy efficiency retrofits. Studying conversion rate variation nationwide can reveal useful details to inform program design.

Population data on FSAs were obtained from the 2006 and 2011 censuses and the National Household Survey^{2,4,5}; these were then matched with household pre- and post-retrofit data. Statistical analyses at this stage have been limited to linear regression modelling, using R's native function.

3. Results and discussions

Variation in the conversion rate nationwide are plotted in Figure 2. At first glance, this suggests greater adoption (marked in green) in higher density areas, with lower density areas demonstrating lesser adoption (yellow to red). However, further examination of three major cities highlights non-uniform conversion within cities.

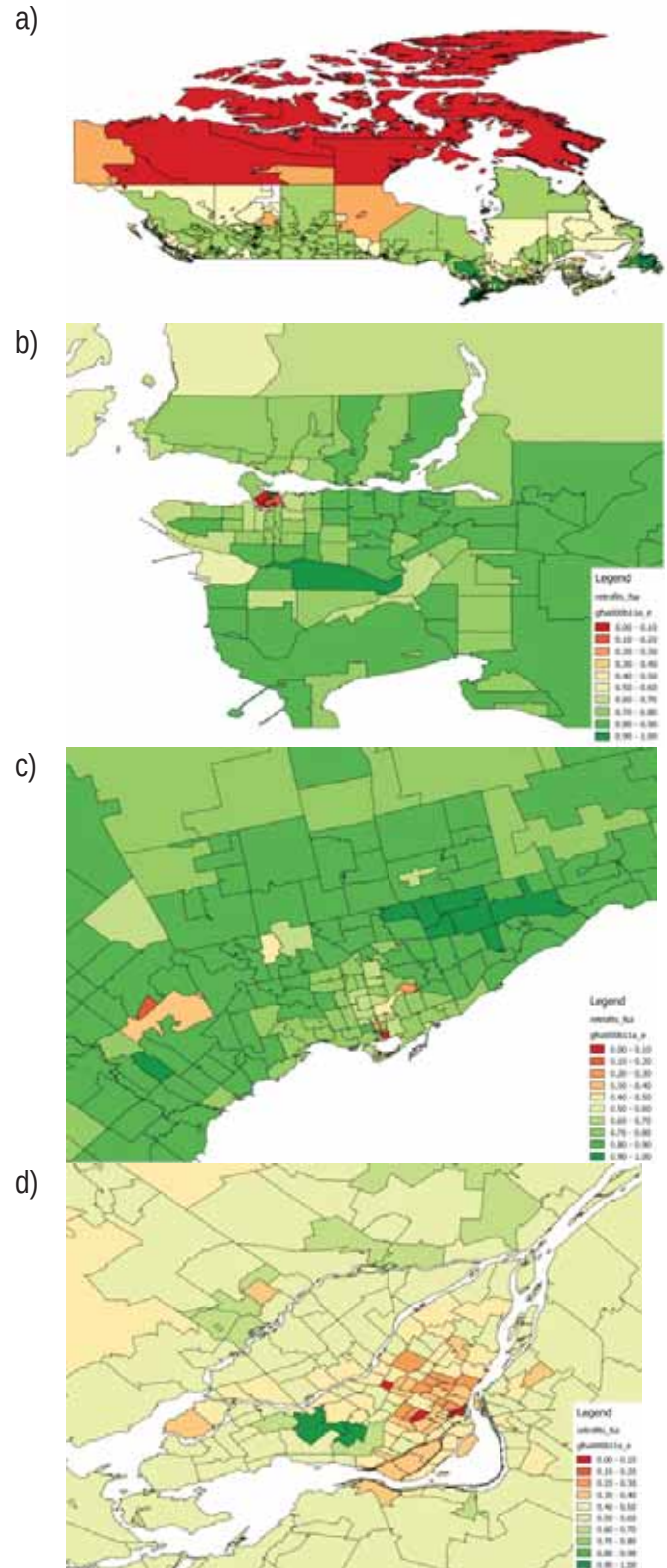


Figure 2: National and Selected Urban Conversion Rates for EcoENERGY Retrofit for Homes; a) Canada, b) Vancouver, c) Toronto, d) Montreal

An examination of temporal adoption patterns (shown in Figure 3) revealed that the majority of retrofits occurred during winter months, with the peak occurring in most jurisdictions at the end of the initial funding period.

Multiple linear regression analysis of the retrofit adoption rate was conducted for all FSAs. This preliminary analysis suggests that income, non-condominium properties, and high shelter costs (greater than 30% of household income) had a significant positive correlation at a 99.9% confidence level (Table 1). Meanwhile, renter occupancy and participation in the workforce were negatively correlated.

Table 1: Multivariate Regression Results for Selected Variables Related to the Share of Single-Family Dwellings Retrofitted in all Canadian Forward Sortation Areas (n=1580; signif codes '****' = 0.001, '***' = 0.01, '**' = 0.05, '.' = 0.1, ' ' 1)

Variable	Estimate
Intercept	9.39x10 ⁻² ***
Pop_density	8.30x10 ⁻⁷
Income	5.71x10 ⁻⁷ ***
Post-Sec_edu	-1.28x10 ⁻²
Workforce_particip	-1.35x10 ⁻³ ***
Non-condo	3.61x10 ⁻² **
House_poor	7.63x10 ⁻⁴ ***
Prop_value	-1.76x10 ⁻⁸
Rent_occupied	-7.12x10 ⁻³ ***

The findings above fit with an emerging pattern that grant programs are simple and effective at delivering high volumes of savings but have a weak market impact in the post-funding period (~25% of energy advisors were laid off after the conclusion of the initial program end date of March 2011)³.

There is a general movement away from this type of 'rebate only' program towards more comprehensive 'market transformation' retrofit programs. This program include elements of the latter approach

(e.g., training for over 5000 energy advisors), but an internal evaluation states that ERfH would have been more cost effective if it had better engaged local partners.

4. Conclusions and outlook

This study reinforces the importance of the upfront cost barrier and consistent federal-level support. However, retrofit program design may need to provide different grants in different municipalities to address specific community needs. The next phase of this study is to use spatial and temporal disaggregation of selected technologies to help guide the next generation of Canadian retrofit programs.

Finally, the spike observed at the end of the retrofit resulted in a boom and bust cycle, which is symptomatic of grant programs.³ This creates labour market volatility in the energy retrofit sector, rather than building a stable market from the ground up. Policies must select incentive levels to create demand growth that can be supported by the market, to avoid distorted price signals and encourage long-term plans for hiring energy assessors. Businesses and homeowners should be encouraged to develop continual improvement strategies for their energy efficiency retrofits, discouraging subsidy expectations.

Acknowledgements

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Creating Low Carbon Cities in the UK - The Future of Civil and Building Services Engineering

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Abstract:

The UK has a legally binding target of an 80% reduction in CO₂ by 2050 compared to 1990 levels. The government's Committee on Climate Change states that this is unachievable without a near complete decarbonisation of the heating sector, which accounts for half of the country's total energy use. Both the problem and the solution lie within cities. This paper explores the ways in which civil and building services engineering can collaborate as disciplines to create low carbon cities in the UK. A literature review describes the scope of the challenge of moving away from hydrocarbons towards electrified heat and transportation. The role of storage and demand side response are explored as strategies to shift peak loads and mitigate the need for electricity infrastructure upgrades. The challenges of retrofitting electrified heat and transport into existing infrastructure are considered, with particular focus on the Balanced Energy Network (BEN) case study at London South Bank University in central London. The BEN case study is a combined heating, cooling, and electricity network that uses ground temperature water to transfer heat between buildings and exploits asymmetric loads to increase the COPs (Coefficient of Performance) of the building's heat pumps. Storage and demand side response links turn BEN systems on and off at optimal times to limit the use of grid electricity. The BEN concept offers a scalable solution that has the potential to be a key tool in delivering low carbon cities in the UK. Finally, this paper discusses the role of the civil and building services engineering as disciplines and how they will collaborate in coming decades. Zero carbon heat is not achievable at scale within buildings themselves. Civil and building engineering projects must be planned together in order to deliver buildings as part of an energy system built on low carbon infrastructure.

Keywords:

Low carbon cities, low carbon heat, heat networks

1. Introduction

The UK is legally bound to reduce carbon emissions by at least 80% by 2050 compared to 1990 levels [1]. This was mandated by the 2008 Climate Change Act and reinforced in the Paris Climate pledges. The government's Committee on Climate Change (CCC) states that this is unachievable without a near complete decarbonisation of the heating sector [2]. Heat accounts for half of the country's total energy use, and government has recently stated that decarbonising the heating sector stands as the country's greatest policy and technical challenge for meeting our climate targets [3]. Both the problem and the solution lie within cities.

This paper is structured as follows. A literature review describes the challenge the UK faces in decarbonising heat in cities as well as the policy and practical pathways to meeting that challenge. The empirical portion of the paper then describes the Balanced Energy Network case study at London South Bank University which offers a practical demonstration of implementing these challenges and the scale of the potential solutions. Finally, the literature theory and the empirical example are brought together to inform a discussion on the disciplines of civil and building services engineering

themselves and how their collaboration will shape the future of energy systems infrastructure.

2. Literature

The UK's target of reducing emissions by 80% by 2050 poses a challenge on a scale that is difficult to absorb. The UK Government's Clean Growth Strategy paints an eloquent picture of the path taken so far [3]. Since 1990 the UK has reduced emissions by 42%, however, of this, around 44% is due to a cleaner power sector, primarily replacing coal with natural gas [4]. While the UK is almost halfway to meeting the 2050 target, the second half will be considerably more difficult, and require drastic changes across a wide range of sectors.

A summary of a recent CCC analysis on the hard-to-reach sectors is given in Figure 1. It shows that few cost-effective savings are likely to be found in the international shipping and aviation sectors, nor in the agriculture sector. They call for halving industrial emissions, which is to come from efficiency gains (e.g. waste heat recovery) and fuel switching, and other means of reducing the impact of industrial processes without adversely impacting UK GDP [3]. These three sectors alone combine to make up 141 MtCO_{2e} of the 165 MtCO_{2e} carbon budget in 2050.

This leaves less than 25 MtCO₂e for all other sectors including buildings (heating), transport, and power, which currently consume at least 310 MtCO₂e.

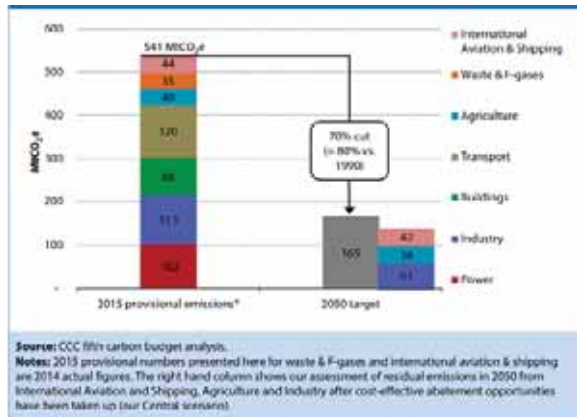


Figure 1: Committee on Climate Change analysis of hard-to-reduce sectors and the 2050 target [2]

This means that heating, transport, and power must be nearly completely decarbonised. The energy system is on the cusp of the greatest changes since the creation of the National Grid, and this places the core of the challenge within cities. Drastic changes will be made not only to buildings themselves, but to the systems and architecture that connect them.

The UK has already pledged to remove unabated coal from power generation by 2025, and renewables are providing an increasingly cost competitive alternative to fossil fuels. The carbon intensity of the grid (currently at ~300 gCO₂e/kWh) is reasonably projected to be below 100 gCO₂e/kWh by 2030, 50 gCO₂e/kWh by 2040, and 30 gCO₂e/kWh by 2050 [5]. While far from simple, there is a relatively visible path towards a low carbon power grid dominated by renewables, new nuclear, and interconnectors.

For low carbon transportation, the UK has already declared that no new petrol and diesel cars can be sold beyond 2040 and many other countries have similar trajectories [3]. There is clearly a role for government in creating the infrastructure required (e.g. charging points), and in supporting take up, however market forces are already driving down the cost of ultra-low emission vehicles (ULEVs). It is predicted that by 2030 anywhere from 30% to 70% of new vehicle sales will be ULEVs [3]. As with the power sector, there is a challenging, but realistic path towards low carbon transportation by 2050.

Heating however, is different. There are a number of factors that combine to make heat the greatest policy and technical challenge in meeting the UK's carbon targets [3]. The UK is a heating dominated country, and aggregate peak demand for heat is roughly five times greater than that of electricity [6]. The literature on low carbon heat transitions is becoming

increasingly populated with useful models, scenarios, and insights; however, none have emerged as decisive and there is currently no clear pathway to low carbon heat by 2050.

Furthermore, regardless of the strategic options chosen, delivering low carbon heat will face the practical challenge of making changes to nearly every individual building the UK. The remainder of this section will break down these challenges, consider the strategic options, and finally the implementation issues, with an emphasis on how this energy infrastructure will develop within cities.

Challenges in Transforming Heat:

The UK's high penetration of relatively cheap natural gas for supplying heat to buildings is an important constraint on the deployment of renewable heat technologies and infrastructure [7] [8]. Around 80% of UK homes have gas fired boilers, and there are approximately 1.2 million new boilers installed each year compared to 20,000 low carbon heating systems [9].

Low carbon heat will require changing the heating system and energy performance of approximately 23 million existing UK homes, and likely upgrading many of the 5-7 million new homes that will be built from now to 2050. The transition to low carbon heat requires working at a rate of 20,000 homes per week for 25 years. The issue is similarly challenging in the non-domestic sector. While we gather evidence for major infrastructure decisions such as the future of the gas grid, there is a preparation phase that requires vigorous action and pilot schemes that increasingly build the evidence base as well as the capacity of the market to deliver a successful transition [10].

The main policy driver for low carbon heat is currently the Renewable Heat Incentive (RHI), which pays a tariff for each kWh of renewable heat generated by a system. Most countries have opted for an upfront rebate to incentivise low carbon heat. The UK is among the only examples of this complex and costlier tariff approach. The RHI increases in uptake each year, however low carbon sources currently meet 5.6% of UK heat, compared to the target of 12% by 2020 [6].

A review of past precedents for large scale heating infrastructure transitions found that a combination of incentives, planning, regulations, and taxation of conventional fuels are essential to the transformation. The UK has ahead of them a period of 3-4 decades requiring a sustained policy effort to bring about this profound shift [11]. One of the key success factors noted is policy stability. This may prove to be the most challenging barrier in a sector that has already seen a number of national scale false-starts (e.g. Green Deal [12], and Carbon Capture and Storage

[13]). The need for stability is supported by both the CCC and the UK gas and electricity regulator - Ofgem, which argue that the near term steps should focus on active experimentation, rather than a 'wait and see' approach [6].

Demand Reduction:

Reducing the total demand for heat is a logical first step in attempting to transform an energy system. Given that between 80% and 90% of the housing stock of 2050 is already here [14], demand reduction is primarily a retrofit problem. The UK has among the oldest building stock in the EU, and among the poorest performing in terms of energy use. The UK has made much progress in addressing this. On average, UK homes now use 30% less energy than 30 years ago, with most of the change being seen since 2004 with an uptake of condensing boilers and energy efficiency measures through government programs [15].

The UK has insulated over 70% of lofts and cavity walls [16]. Most of what remains is classified as hard-to-treat measures such as solid wall insulation that face a number of cost and implementation barriers.

Some studies suggest that the remaining theoretical potential for improved energy efficiency is 25% across the housing stock based on a thorough uptake of cost effective measures [15]. A less optimistic picture can be obtained by taking the metered savings achieved by the measures installed so far, and extrapolating this to the remaining homes. With this estimate the UK can expect no more than 10% savings across the stock. This means that at most anywhere from 10% - 25% savings can be achieved through demand reduction. Again, noting that these figures apply to the domestic sector, but that the issues are broadly similar in the non-domestic sector as well. Demand reduction is therefore an essential, but limited component of delivering low carbon heat by 2050.

Electrification versus hydrogen:

There are two core options for low-carbon heating fuels: electricity served by a green grid and carbon free gas. Consider first the electrification of heat.

Electrification of heat primarily refers to heat pumps. There are potential efficiency gains through enabling technologies such as heat networks that will be discussed below. Heat pumps currently represent a minute fraction of heating in the UK (~2%) but there are calls to increase uptake by over 2 million units (or 30 TWh) by 2030 [17].

Heat pumps face a range of barriers in the UK from high upfront costs to low consumer confidence in the technology. Aside from these implementation issues, the core infrastructure challenge to heat pumps is the increase in peak loads that it imposes on the grid.

This is the subject of much study, but also much uncertainty given the range of unknowns. If heat pumps were to make up between 60% and 80% of UK heat, then the increase in grid peak loads could be anywhere from 20% to 100% depending on the use of the thermal storage and smart controls [18].

The main alternative to electrification is carbon free gas. This typically means a green gas such as biomethane, or hydrogen. Biomethane production can only meet a small fraction of UK heat demand. Hydrogen has higher potential for scalability. Industrial scale hydrogen production typically comes from either electrolysis, steam methane reforming (SMR), or in small amounts as a by-product of other processes [6].

Electrolysis requires considerable electricity use, and would likely need to be paired with a power source that would otherwise be curtailed (e.g. excess wind at off-peak times). The need for low cost electricity could lead to a high capital investment with abatement curves that depend on small operating windows.

SMR is likely the preferred option [6]. SMR requires large scale plant to convert natural gas into hydrogen and capture the carbon dioxide at source for sequestration. Hydrogen could then replace natural gas in the existing distribution pipework. Due to the inherent similarities with gas, it is argued that this would represent a less intrusive transition for end users than a switch to heat pumps or heat networks [6]. It does however face many practical hurdles including:

- Natural gas using appliances would require replacements (most of which currently do not exist).
- Both SMR and CCS technology is currently underdeveloped.
- There are considerable safety testing issues for every step in the new hydrogen supply chain.

The theoretical as well as practical issues are currently being actively explored through the pilot H21 Leeds City Gate project. This is a study which aims to determine the technical and economic feasibility of converting the existing natural gas network in Leeds to 100% hydrogen [19]. The UK government is undergoing an extensive evidence gathering process and aims to decide the future of the gas grid by 2025 [3].

Smart-grids and multiple energy vectors:

Ultimately low carbon heat will be a combination of electricity and carbon-free gas. Operational flexibility will be at the core of a cost-effective and low carbon energy system [20]. The terms 'smart-grid' and 'multiple energy vectors' are frequently invoked to explain this new paradigm.

While definitions of smart-grids vary widely, the common principle behind them is a bilateral flow of information in a network. The system until now

largely consisted of centralised generation and one-way transmission to end users. This is evolving to include distributed renewables generation, distributed storage, utility scale renewables, utility scale storage, and is also converting from radial networks to mesh networks. There is also a layer of communication networks that enable more intelligent control of these distributed resources. [21]

The transition to a low carbon economy will force us to rethink how buildings exist as actors in advanced energy infrastructure. In this it is critical to move beyond historical operation and design principles [20]. There is a crucial opportunity to move from security that is largely delivered through costly asset redundancy towards smart corrective control measures that enhance the utilisation of existing assets and a more cost effective integration of low carbon technologies [20].

There are likely to be very significant levels of investment required for network reinforcement in the coming decades. Strbac et al. [20] recommend looking beyond like-for-like replacements and instead consider the strategic options to avoid constraining future systems. For example, holistically considering energy delivery, emissions, losses, and needs for ancillary services and security of supply. Energy storage technologies and interconnectors with continental Europe will be an important tool enabling large-scale sharing of energy and backup resources [20].

Demand side response (DSR) is a type of virtual storage that can redistribute consumption and engage demand side resources as balancing services to enhance flexibility [20]. DSR use is currently small, approximately 1.3-1.6 GW in 2015/16 [22] but it is a rapidly increasing area of interest for academics, policy makers, and entrepreneurs. The CGS pathway suggested that 70% of extra capacity and flexibility by 2032 will come from DSR [3], and a study found that over the next 50 years, DSR could deliver a cost savings of £60 billion for the UK power system [23].

Incorporating storage and DSR into energy models of low carbon cities is an essential, and increasingly popular idea, which has led to numerous models exploring the field of interactions across energy vectors such as gas and electricity, or heating and transportation. The need for coordination across energy vectors is seen as inevitable [20] [24], and if properly embraced represents an opportunity to more cost effectively incorporate low carbon innovations. Multi-vector models have shown for example the need for embedded storage alongside distributed generation [25], and how flexible investments can reduce the cost of delivering smart grid assets that can be coupled, controlled, and optimised [26].

The need for smart grids and multiple energy vectors is likely to lead to an expanded role for enabling

technologies such as heat networks. In particular, it has the potential to expand the range of what typically constitutes a heat network to include distributed storage, heat sharing, and DSR based control systems [27]. This literature review has broadly described the theoretical options and challenges of low carbon heat in cities, but finds that there are critical gaps in understanding feasible transition pathways. A case study will explore one such transition for two buildings in central London.

3. The Balanced Energy Network (BEN) at London South Bank University (LSBU)

LSBU is located in the heart of London and contains a representative cross-section of UK building stock in terms of use and form. Lessons from retrofitting low carbon heat at LSBU are therefore widely applicable to many cities across the UK. BEN is a demonstration heating, cooling, and electricity network that balances the delivery of these three services in a way that aims to minimise costs and carbon emissions.

At its core, BEN uses a 'Cold Water Heat Network (CWHN)' [28] designed by ICAX Ltd. to move and store energy between two buildings on the LSBU campus. Both buildings are both approximately 10,000 m² and the heating requirement is currently served by a gas fired boilers operating in a cascade. The BEN project will retrofit a 95kW_e (300kW_{th}) high temperature heat pump in parallel to the existing gas fired boiler system of each building.

The principle of a BEN style heat sharing network is to reject heat to the network from a place that needs cooling and recover the heat in those needing heating and domestic hot water. Exploiting asymmetric loads between buildings has the potential to increase the heat pump coefficients of performance (COPs), however, when the buildings share similar loading characteristics, the network requires a method of regulating the temperature of the ground water loop. In this case, BEN's CWHN is linked to two boreholes, which use water from the chalk aquifer beneath London (with an average temperature of 13°C). BEN systems are managed by a cloud based aggregator (Upside Energy), linked to the network system controller, which together deliver DSR. The DSR aggregator communicates with hot water tanks specially designed by Mixergy to create a smart storage solution, and the ICAX controller which interfaces with the existing and new plant. [27]

Finally, BEN also links with a unique fuel cell calciner (produced by Origen Power in collaboration with Cranfield University) that creates carbon negative electricity by actively removing CO₂ from the atmosphere [29]. The heat from the fuel cell breaks down limestone (CaCO₃) into pure carbon dioxide (CO₂) and lime (CaO). It is estimated that all of the CO₂ produced from this process will be 99% pure and

can be economically geologically repossessed, the cost of purification being a significant issue with carbon capture and storage technologies. The lime (CaO) produced during the process will be converted to CaCO_3 by absorbing CO_2 from the air [29].

The BEN approach to heat network design does not require an energy centre. There is no central generation and distribution of heat, rather it uses heat sharing. This means that heat rejected from one part of the network can be exploited as heat in another part of the network. This could be rejected heat from cooling plant, a data centre, or even low grade waste heat from sewers or the London Underground system. All of these add resilience to the system and do not require planning in advance. A new development at the feasibility stage would have the option of creating a standalone building services strategy or linking to a nearby BEN system if this is more efficient.

The central idea is that BEN is an integrated, multi-vector energy network that can provide heating, cooling, and electricity by linking them through distributed storage. It can then manage the delivery of each service using smart-grid principles, in this case a DSR based control system that makes use of dynamic time of use pricing signals. This can optimise the delivery of all three energy vectors with the least cost and carbon emissions.

The process of demonstrating the BEN system in central London has highlighted many practical limitations of retrofitting an integrated energy system within cities. There are challenges at the building scale, such as how to manage a crowded plant room and integrate a new heat source into an existing distribution system. At the urban scale, BEN required not only a suitable place for the boreholes, but also for the pipework connecting the buildings. This is a nontrivial challenge in a densely packed urban area. It faces not only challenges at the ground level, finding access space for equipment, deliveries, and other construction logistics, but also constraints below the surface. Any drilling projects require a deep services survey and knowledge of underground water mains, electrical works, gas networks, unexploded ordinance, and the underground subway and cross-rail systems.

The initial BEN plan called for underground pipework in a trench 1m deep, but surveys found that the ground was too congested with existing services to find a suitable route. Instead, the pipework was mounted to the walls of the buildings above ground. This was only an option because we were using the lightweight, lower grade plastic pipework that an ambient temperature network permits. If the network had been a more conventional medium-high temperature network with higher grade, insulated pipework, then this would have been considerably limited.

The BEN demonstration project show that there is actually great flexibility in how you link up buildings, but that it requires considerable coordination between parties.

4. Discussion: Coordination between civil and building services engineering

Finally, this paper considers role of the civil and building services engineering as disciplines and how they will collaborate in coming decades. The world's cities account for about three quarters of global carbon emissions [30]. There are a number of efforts driving innovation at the city level. In 2016 the charity CDP convinced 533 cities to disclose climate change related data. They use the data to facilitate networks, particularly to access private sector investment to support city green infrastructure projects. In the UK, the UK100 effort has 78 local leaders committed to 100% clean energy by 2050 [31].

Zero carbon heat is likely not achievable at scale within buildings themselves. Civil and building engineering projects must be planned together in order to deliver buildings as part of an energy system built on low carbon infrastructure. In the UK, professional accreditation for engineering disciplines are handled separately by the Institution of Civil Engineers (ICE) and the Chartered Institution of Building Services Engineers (CIBSE). These two organisations have created a collaborative task force on the issue of low carbon heat.

The policy and modelling fields of multiple energy vectors can be implemented through systems such as BEN. What this demonstration project has highlighted above all else is the coordination between disciplines that will be required to deliver low carbon heat at scale. Linking buildings together in a way that doesn't exceed local power capacity (or at least minimises the need for reinforcement infrastructure) requires understanding across disciplines.

Projects such as BEN, which pull heat from the ground, if implemented at sufficient scale, will also face constraints of heat removal from soil. At some point a heat sharing network like BEN will create a situation where the removal of heat from the ground at one point in the network negatively impacts the performance of the neighbouring ground source system.

Planning the constraints of a local power substation or the storage and transfer of heat through the ground is not a task for individual building projects. Energy management across an estate such as a university campus, housing development, or hospital estate will become increasingly common, and its success will depend on early stage discussions between civil and building services engineers to understand how the heating, cooling, and electrical, and even water systems can work together most effectively.

Collaborations such as that between the ICE and CIBSE will be essential in building the professional networks and knowledge to enable this.

5. Conclusions and outlook

Low carbon cities are the great challenge for the 21st century. In the UK this is above all a heating challenge. There are a number of theoretical options, but no preferred pathway. Ultimately the solution will be a combination of options including the electrification of heat and transport, and a use of carbon-free gas such as hydrogen. It is widely agreed that delivering this combination cost effectively will require a revolution in energy infrastructure, particularly making use of demand reduction, storage, demand side response, and better integration of smart systems across multiple energy vectors. The BEN case study shows that that delivering these upgrades within cities is a challenge, but a manageable one, and that early efforts should focus on replicable demonstration projects that can expand organically over time.

This paper has argued that with the transformation to a low carbon heating system buildings will be thought of not as standalone energy users, but participants in an energy system. Estate energy management will recover and share heat across stores and require a deep collaboration and even integration of engineering disciplines, particularly civil and building services engineering.

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Turning National Retrofit Policies into Local Action: Examples from the US BBNP and the Canadian Eco-Energy Programs

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Abstract:

Improving energy efficiency in existing dwellings is critical in efforts to address climate change. National level retrofit policies are useful for delivering large volumes of funding with a coordinated program brand. However, for countries such as the US and Canada, energy issues vary considerably nationwide and are therefore governed at the state or provincial level. Finding ways to calibrate national level policy objectives and structures for effective delivery at the local level is a critical policy priority, but is poorly understood by policymakers and underrepresented in academic research.

This paper addresses this gap by analysing the US Better Buildings Neighborhood Program (2010-2013), and the Canadian Eco-Energy Retrofit Program (2009-2013). Both of these programs were created with a national level overarching structure and objectives, but were implemented in different ways at the state/provincial and local levels. The impact evaluations of each program found that they were broadly successful at the national level. This paper considers how each program targeted local action along three themes. 1) Housing stock factors including population, social, and demographic issues inherent to the spatial distribution and fundamentally unchangeable. 2) Program design factors consider issues such as leveraging local funding and resource pools. 3) Program delivery factors include implementation strategies for driving demand and workforce engagement.

The results suggest that demographic factors are not predictive of overall program success (measured as total upgrades and/or energy savings). Effective program design and implementation can compensate for housing stock factors. A set of best practice principles are described for adapting national level program structures for effective local program delivery.

Keywords:

Domestic retrofit, policy design, program implementation

1. Introduction

Barriers to domestic retrofit have been the topic of extensive study both in academia and in policy making for decades (see e.g. [1] [2] [3] [4]), Arguably one of the most interesting aspects of this issue is that it is still in fact an issue at all. Decades of research could be distilled to say that thermal retrofits have yet to find a sufficiently compelling value proposition for homeowners. This does not suggest that there is no value, only that the perceived benefits to homeowners are insufficient to overcome the barriers present [4]. Given the longstanding nature of these barriers any treatment of the topic at this point must also consider how the considerable body of knowledge on the topic has so far failed to sufficiently address the issue.

This paper will argue that a great part of this failure is due to a lack of coordination between national and local scale action. National scale ambition is essential for market stability, and local action is equally essential for market implementation. Mapping national frameworks to local circumstances is subtler than it appears and is an area of policy and program design that is worthy of dedicated attention.

To that end, this paper will begin with a brief summary of the most relevant barriers, focusing on why these remain particularly entrenched in the able to pay market. It will introduce two case studies, the Canadian ecoENERGY Program and the US BBNP. The method of analysis is given. Best practice principles for translating national policies to local action are discussed along three themes: 1) Housing stock factors, 2) Program design factors, and 3) Program delivery factors.

2. Literature

Policies based on price signals and conveying the benefits of improved comfort have convinced the early adopters in most retrofit markets but have failed to drive self-sustaining changes at scale. The core barriers of the low priority of energy issues, information asymmetries, upfront cost, and split incentives have not fundamentally changed in decades of study and political action [3] [5].

One notable change in retrofit program design since the 1980s has been a gradual shift away from demand side management (DSM) programs towards market-based, whole house approaches. DSM

programs typically have discrete objectives such as deploying energy efficient lighting [6], boilers, and insulation. This is critically distinguished from market transformation, which targets changes in market effects over time [7]. Due in part to supply chain fragmentation and the pervasive nature of the barriers present, programs seeking a whole house approach are required to be more comprehensive than the DSM programs of the past.

It has been shown that a retrofit program whose design is solely based on the provision of grants will stimulate the market only as long as the grant remains. Once the grant is removed, the market effect is likely to disappear [8]. Some markets can be maintained through programs such as the Weatherisation Assistance Program in the US, or a number of Efficiency Obligation schemes across the EU. However, these programs largely target the social housing sector, and many countries are reluctant to similarly support able to pay markets. Most policies targeting the able to pay market are created as temporary subsidies with the aim of kick starting self-sustaining changes [9] [10].

In order to avoid the 'boom and bust' cycle of removing a grant and losing the market impact, programs are becoming increasingly sophisticated in how they stimulate not simply kWh savings, but changes in critical market effects such as levels of knowledge, workforce skills, and data gaps. In the past decade the EcoENERGY program in Canada and the BBNP in the United States were created with the stated objectives of supporting able to pay retrofit markets. These offer considerable insight in how modern retrofit programs are transforming markets with a national scale vision calibrated through local delivery.

3. Canadian ecoENERGY Program

The ecoENERGY Retrofit for Homes program ran in several phases nationwide from 2007-2012. It offered over \$1 billion CAD in grants (up to \$5,000 per household) for efficient heating appliances, insulation, windows, doors, air sealing, HVAC systems, and hot water heaters [11].

Energy advisors carried out home energy audits for over 640,000 single-family homes and over 90,000 homes received grants and successfully installed retrofit measures, which EcoENERGY credits with 0.32 Mt of GHG emissions reduction [10] [11]. This corresponds to a savings of \$400 million on annual energy bills and an average 20% reduction in energy consumption for participant homes [12]. A parallel research effort has found that while the program was largely successful overall, results varied considerably nationwide. An early review of this data suggests that retrofits were not adopted with spatial or temporal uniformity (see Paper #052).

4. US Better Buildings Neighborhood Program

The US BBNP was created with the aim of kick-starting the economy in a way that also drove energy efficiency and thermal retrofit markets. They awarded a total of \$508 million to 41 state and local programs which ran from 2010 to 2013. While the objectives of the ecoEnergy Program were more broadly stated as 'encouraging homes to be more energy efficient' [10], the US BBNP specifically targeted a permanent transformation of retrofit markets and awarded grant money based in part on the proposed strategy to sustain program activity beyond the grant period [13].

The BBNP was successful against nearly every stated objective, upgrading over 100,000 residential and commercial properties, creating over 10,000 jobs, delivering an average savings of at least 15% in energy costs per home upgraded, leveraging nearly \$1.4 billion in private sector investment, and creating a lasting market impact with 84% of grantees continuing program elements in the post funding period [14].

5. Method

This paper analyses the Canadian ecoENERGY and US BBNP programs using the programs' own evaluation reports [10] [11] [14] [15] as well as supporting third party analyses such as net to gross studies [16] [17]. Existing research conducted on individual grantees or program elements will be referenced throughout.

Based on this document review, three themes were identified as particularly relevant for translating national policies into local action:

- Housing stock factors including population, social, and demographic issues inherent to the spatial distribution and fundamentally unchangeable.
- Program design factors consider issues such as leveraging local funding and resource pools.
- Program delivery factors include implementation strategies for driving demand and workforce engagement.

Based on the principles of success described in the program's own evaluation documents a set of best practice principles were distilled along these three themes using examples from each program as appropriate. As a qualitative study based on case study evidence, the findings are inherently limited in terms of external validity. However, the aim is to describe the extent to which the variables in each theme are linked to overall program success and note where they may hold wider relevance to retrofit program theory.

6. Analysis

Housing stock factors:

There are a number of program demographic factors inherent to the location of the program that cannot be fundamentally altered, but can critically impact how a program performs. For example, population, housing type, income distribution, levels of knowledge of both homeowners and the workforce, and the status of pre-existing programs to name but a few. Given that these factors will vary nationwide, it can be difficult to craft a national level policy with suitable relevance and fairness across the range of circumstances. The critical success factor at the national level is to allow local programs the flexibility to calibrate their programs to their own local markets.

With 41 program grantees across the US, the BBNP was faced with an extremely broad demographic and policy landscape. Grantees proved that nearly any program can be successful if suitably designed for the local circumstances [14]. The South Eastern Energy Alliance for example hosted many programs in areas with little to no prior experience in energy efficiency, few pre-existing programs, and below average levels of household income. The program was designed around these factors and featured heavy workforce engagement and training at the outset, and focused higher levels of subsidies on suitable technologies to overcome cost barriers [17].

The BBNP program structure at the national level was well designed to encourage this type of local calibration, with grantees setting out their own objectives and strategies to meet those objectives. The ecoENERGY program by contrast was more uniform across the country, with grants set at the national level [11]. 12 of 13 provinces and territories offered complimentary incentive programs [12], but in a less coordinated manner than the BBNP.

Local program design factors:

There are a number of factors which fall under the theme of local program design, but this section will focus primarily on how the program identified its market niche and leveraged the support of surrounding networks. In this area there are several best practice principles to draw upon from the two case study examples.

Finding a suitable market niche requires striking the balance between the national and local brand for the program. Some BBNP localities find that national brands embody trust and consistency while others value local identity. This also varies by brand. Some BBNP grantees existed in areas with low confidence in the brand offered by the federal energy program, but a high confidence in the national level Building Performance Institute (BPI) brand that certified the skills of the participant workforce. Efficiency Maine for

example found that both the program and the BPI were trusted brands and created hats that contractors could wear to identify themselves as program participants when working on BBNP projects.

In ecoENERGY, the Federal Home Renovation Tax Credit (HRTC) was seen as having a positive impact on uptake of the ecoENERGY program. The credit essentially allowed a double incentive to renovate. While there was confusion over the mixed branding of the offers, when ecoENERGY operatives were approached about HRTC, they were able to explain that both programs could be used together. HRTC thus served as an additional route to market for the ecoENERGY program and brought in homeowners that it otherwise may not have [16].

The other local program design factor that was critical to success was the degree to which the program embraced and collaborated with pre-established networks in the community. This could range from trade groups, credit unions, or community groups with no history of activity in housing. The success factor was creating the networks, often based on individual relationships, that enabled the program to extend its reach in the community and calibrate its activities in the most suitable manner. This local presence should include local workforce and could not be entirely made up of external program employees, as several grantees found that these were perceived as outsiders.

Program delivery factors:

This final theme deals with local program delivery. Once the program goals are suitably calibrated and the local networks are in place, success was driven by how well these networks identified and addressed the barriers at a local level. While the program brand or traditional marketing such as tv and print ads were useful for generating leads, they were not sufficient to convert these leads into retrofit action unless accompanied by a more personal outreach campaign [18]. This often meant an individual level, with program organisers creating personal engagement strategies to speak to homeowners, understand their needs, and help the program address these needs.

Similarly, program organisers found that engagement with the participant workforce was equally essential. Many retrofit markets are at such an early stage of development that it is necessary to stimulate the supply push as well as the demand pull. Contractors would need to be persuaded to undertake new energy efficiency work in addition to their business as usual home renovation portfolios [18]. If this required new skills, new staff, or new equipment, the program had to respond to these needs to ensure that a suitably qualified workforce was available to meet demand. A key success factor for the ecoENERGY program was the presence of an energy assessor in the home to directly answer homeowner questions. 69% of

respondents learned something new from their energy advisor and report, and 76% said that it helped them decide which retrofits to implement [11].

Here again, the circumstances varied enormously by location and the best practice principle at the national level was to give local programs the flexibility to spend program funds as they saw fit, even if that was on directly paying for training the workforce. The use of public funds for developing skills in private trades is controversial. Some feel that this is an area best addressed by market forces, with a baseline performance maintained through building codes and standards. While this might hold true for well developed markets given sufficient time, if program designers want to deliver a high volume of quality retrofit projects and increase the perceived value of retrofit within program timescales, then investing in skills development is all but essential.

EcoENERGY found that mid program, they faced shortages of energy advisors to conduct the home energy assessments, which created bottlenecks and prevented homeowners from accessing the program. They successfully addressed these capacity issues with a recruitment and training campaign [19]. The program trained more than 2000 energy advisors [12]. ecoENERGY found that most uptake was from people already planning to do a renovation and who wanted some guidance. In many instances contractors alerted them to the program [16]. This principle of contractors acting as the salesforce driving the program was common in the US BBNP as well [14], and many evaluations have found that this type of engagement with the workforce is essential to embedding the skills and practices of thermal retrofit alongside their existing home renovation work. This is a critical to leaving a lasting program effect beyond the funding period.

7. Results and discussions

In the case of the US SEEA program they successfully acknowledged gaps in their supply chain early in the program design process and focused efforts on driving training programs. They also acknowledged that certain parts of their state had a lower median income than neighbouring areas and that definitions of 'able to pay' required a subtle and bespoke set of financial incentives for local circumstances. Despite seemingly unfavourable demographic factors the program was among the successful BBNP grantees.

The program design factors considered how well the program leveraged local support and networks. Here the results distinctly show that national level programs should empower and support local partnerships, particularly with the aim of creating networks that can continue in the post funding period.

Program delivery required leveraging those local actors as trusted messengers to create program momentum. Engaging the workforce as program partners can help identify and address gaps, and also embed skills and practices in the local workforce that endure post program.

A critical difference between the US BBNP approach and the ecoENERGY program was that the BBNP competitively allocated funding to localities. Grantees had to identify their own barriers and design suitable solutions, this gave them considerable flexibility in allocate program funding where it was needed most.

The ecoENERGY program by contrast was more uniform nationwide, and served as an add-on to separately crafted local solutions. The common thread across the three themes explored in this paper is flexibility. The US program model favoured this flexibility and offers a useful program template for translating national program objectives and structure into locally suitable solutions across a very diverse nation.

8. Conclusions and outlook

Overall, in both Canada and the US, the national brand was useful for driving awareness with things such as the availability of funding, branding skills, and getting word out. But awareness didn't translate to delivery unless there was a strong local engagement that made use of existing networks, trusted messengers, and local knowledge. National scale retrofit programs should acknowledge this, and use their leverage to create a national brand for retrofit programs, but give local delivery bodies the autonomy to adapt that brand in the way they see fit.

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A framework to assess the performance of indoor swimming pools in Canada

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Abstract:

Indoor swimming pools are becoming popular in countries like Canada due to extreme cold climate. Any compromise on the performance of indoor swimming pools can result in severe health and environmental issues in addition to economic burden. There is a need to conduct the performance assessment of facilities to achieve the maximum efficiency in terms of minimizing health, environment and cost risks by continuously making improvements. This paper proposes a PDCA-ISP (Plan, Do, Act and Check for Indoor Swimming Pool) framework to achieve the targeted performance. This framework comprises of four phases which will provide a better template to facility managers and decision makers in taking the decisions with respect to improving performance of swimming pools.

Keywords:

PDCA framework, indoor swimming pools, performance assessment, continuous improvements

1. Introduction

Indoor swimming is considered as one of the most preferred leisure activity. It attracts a huge number of users as compared to outdoor pools [1], [2]. In Canada, recently there has been considerable upsurge in developing indoor swimming pools due to the cold weather conditions[1]. Most of the people are using swimming pools for sports, recreational and rehabilitation purposes [3]. Approximately 36 million people visit pools per month in Canada [1] and this growing trend is directly contributing to the quality of indoor swimming pools due to the release of organic content [4]. This has resulted in the formation of DBP's (Disinfection by products) which are believe to cause several health problems such as respiratory problems [5], eye irritation [6] and cancer [7] among swimmers and lifeguards. Another major concern is related to environmental impacts which includes, increase in energy consumption and deterioration in impacting water and air quality. Both health and environmental impacts results in economic burden of a facility. Therefore, health, environment and cost are considered as important aspects which need to be assessed, managed and continuously improved along with their interactions with each other for achieving the absolute performance [8].The maximum efficiency of a facility can be achieved by conducting a performance assessment and for an effective performance assessment, a framework should be developed. This study proposes a conceptual PDCA-ISP (Plan, Do, Check and Act-Indoor Swimming Pool) framework by incorporating PDCA principles that are recommended in ISO 14031 [9]. The proposed framework will leads to the continuous improvement and will provide a

template for the performance assessment of indoor swimming pools of Canada.

2. Plan-Do-Check-Act (PDCA)

The concept of PDCA started in 1950 by W. Edwards Deming and Walter Shewhart for the continuous improvements of organizations and institutions at small scale [10].The PDCA is a process in which current condition of a facility is compared with the set targets by facility managers or decision makers. If a difference is identified, it will be indicated and suitable corrective measures will be taken to improve the facility in a continuous manner. This cycle is known as PDCA [11] cycle and also known as PDSA (Plan, Do, Study, and Act) or Deming circle, which is named after W.E. Deming [12]. The purpose of PDCA is to prevent the repetition of error by continuously improving the processes of a facility. In addition, it will investigate and eliminate the root cause of the problems, to improve the efficiency of the system[13]. The improvement actions of this dynamic cycle are categorized into four phases: plan, do, check and act [14],[15],[10] as shown in Fig.1. The use of PDCA cycle by a facility, ensures that facility managers are committed to adopting for the better methods for improving the performances [11]. The application of PDCA has been adopted in the fields of academia and industry at various levels [14] for example, performance improvement of hospitals [16],[17], waste management practices in institutions [18] and in improving the environmental processes [19]. More recently, the concept of PDCA has been used in energy optimization [19],[20] and also as service assessing framework to achieve better quality of service [21]. In some cases, this framework was also used as performance framework by incorporating triple bottom line approach for corporate sustainability [22].

Although, a PDCA framework has been used in many fields for the continuous improvement, there has been no study in the context of performance assessment of the indoor swimming pools. This paper focuses on the development of PDCA-ISP framework for an overall performance assessment of indoor swimming pools.

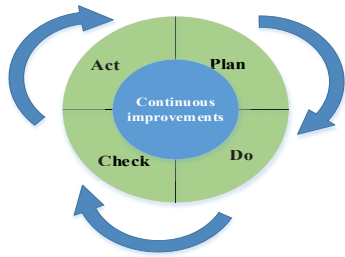


Fig 1: Phases of PDCA Cycle[14]

3. Proposed framework

The proposed PDCA- ISP framework, shown in Fig. 2, is designed to evaluate the overall performance assessment of indoor swimming pools in Canada. This will ensure the efficiency of indoor swimming pools with minimum impacts on health, indoor environment, and associated costs. It comprises of the following four phases:

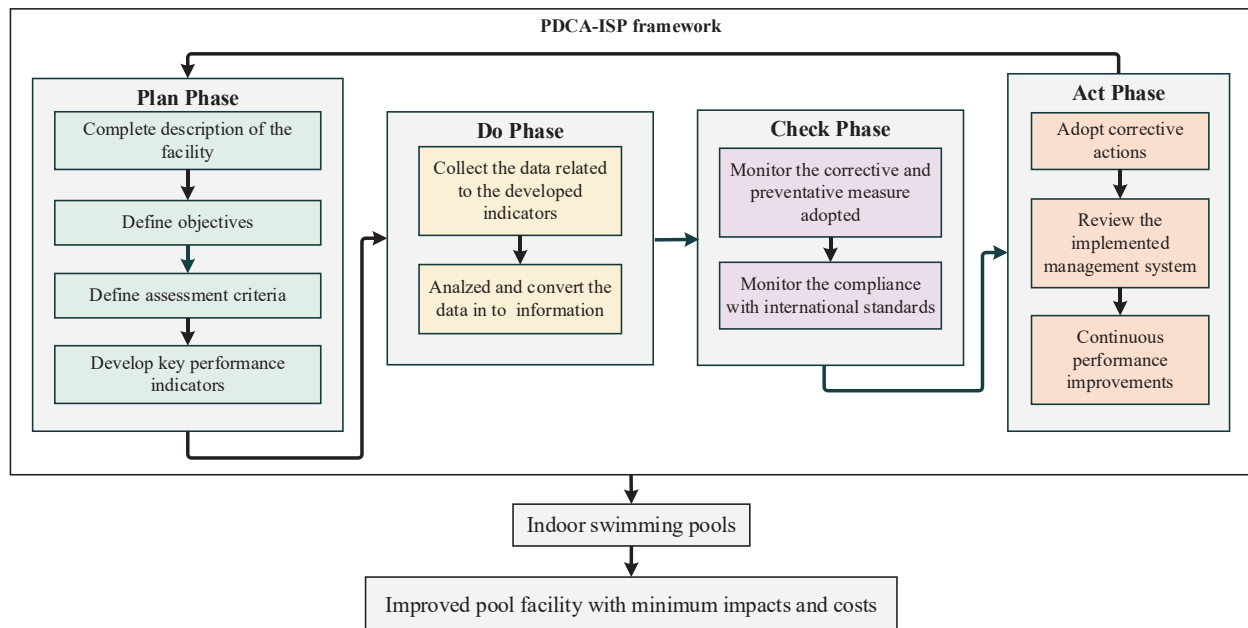


Fig 2: PDCA-ISP framework for the continuous improvements

3.1 Plan

The first phase is plan, in which the key performance indicators are developed in the light of existing literature to achieve the certain objectives of indoor swimming pools. Phase 1 is further categorized into four steps.

Step 1. Carry out a plan for the performance assessment by taking into account information related to the processes carried out previously. For example, information regarding public and occupational health incidents, treatment techniques applied and

environmental quality etc. that is gathering of all relevant information to evaluate the current performance of indoor swimming pool facility.

Step 2. Define the objectives that need to be adopted, to achieve the efficiency of indoor swimming pools and the user satisfaction. These objectives can be in the form of improving the water and air quality of a pool facility, quality of service, minimizing the health impacts, and reducing the economic burden.

Step 3. Formulate the assessment criteria related to the defined objectives, for example, bathing water

quality, health, safety, operation and maintenance. The purpose is to determine whether objectives of a facility are met or not. These assessment criteria can be linked with more than one objectives, for example, bathing water quality can be linked with water quality and also with human health.

Step 4. Develop the key performance indicators which will measure the performance of a facility with respect to the defined objectives and criteria. These indicators will help a facility manager in taking necessary decisions for improving the performance of a facility.

The above steps are further explained in Fig 3

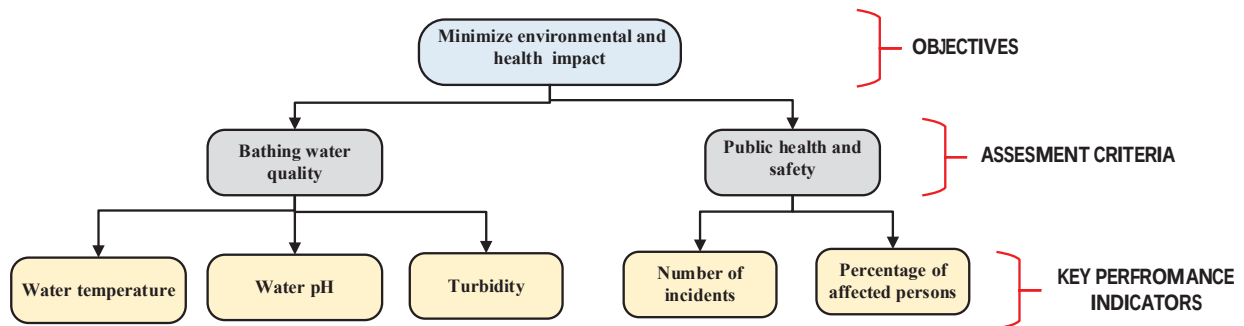


Fig 3: Example of plan phase

3.2 Do

The data related to the developed or selected indicator is collected in this phase, for example, data related to water quality before and after treatment, operational activities that are occurring in the facility, and data related to the performance monitoring. This collected data will be analyzed and converted to the qualitative information to assess the performance of the facility. Further this information will be compared with the defined objectives in Step 2 of Subsection 3.1.

3.3 Check

Here, a facility is evaluated to assess the efficiency in terms of preventative and corrective actions. For example, evaluation of different training programs for manager and lifeguards and monitoring of water quality. In addition, all the processes are examined to ensure whether they are following the international regulations.

3.4 Act

This phase comprises of the following steps:

Step 1. Apply the corrective actions after collecting information from the check phase to ensure that corrective measures are taken to mitigate causes of the identified problems. For example, eliminate the causes of deterioration in the water quality.

Step 2. Review the existing management system to evaluate the current management practices. It helps in identifying the management related issues and suggesting improvements in the management system.

Step 3. The final step involves continuous improvement which is the key of the PDCA framework. This can be

achieved by improving the deprived processes to increase the overall performance.

All of these four phases are interlinked with each other and will help the indoor swimming pool team (facility managers, decision makers, engineers, operators etc.) in achieving the desired performance.

4. Conclusion

Indoor swimming pools are of high significance with respect to health, environment, and economic aspects. There is a need to evaluate all these aspects, to achieve the maximum efficiency at minimum cost. This can be achieved by implementing the continuous improvement strategies and principles such as PDCA cycle. The proposed PDCA-ISP framework will help in achieving the desired objectives of overall performance assessment of a facility. This framework is simple, easy to apply and can be easily adopted by management to improve the performance of a facility. This framework will help the swimming pool managers, operators, engineers, decision makers and researchers who are involved in the continuous improvements of indoor swimming pools. Further research is needed to implement the proposed PDCA-ISP framework in indoor swimming pools to evaluate its effectiveness. It will help in the development of best management practices through the continuous improvements.

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A Review on the investigation of impact resistance of rubberized concrete containing recycled concrete aggregate

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Abstract:

Production of green concrete is a topic of immense interest in the whole world at present times owing to the high level of carbon footprint, particularly in Canada. Incorporation of rubber particles, derived from recycled waste tires and recycled concrete aggregates (RCA), produced from demolished old structures as partial replacements of fine aggregates (FA) and coarse aggregates (CA) respectively in concrete can substantially contribute towards achieving this goal. However, only limited researches have been conducted to date to determine the dynamic properties particularly, the impact resistance of rubberized concrete containing RCA. As such, a comprehensive review of the existing studies focusing on the determination of impact resistance of concrete containing crumb rubber (CR) and a combination of RCA and/or fiber with CR is presented in this study. Studies show that rubber particles enhance the energy absorption capacity of concrete and thus the resistance under impact loads. Moreover, a combination of RCA with CR also results in higher toughness than conventional concrete. Importantly, the addition of fiber to rubberized concrete imparts in a positive synergy between the two resulting in a much higher energy absorption capacity of the resulting concrete. Furthermore, fiber, when added to recycled aggregate concrete (RAC), improves its impact resistance compared with that of RAC. Overall, the use of a combination of CR, RCA, and/or fiber will result in an innovative sustainable material with enhanced energy absorption capacity than the conventional concrete.

Keywords:

Crumb rubber, recycled concrete aggregate (RCA), impact resistance, energy absorption capacity

1. Introduction

The low-strain capacity of concrete, in other words, the brittle nature of concrete makes it vulnerable to resistance against extreme loading conditions in case of natural hazards as earthquakes or winds. In addition, man-made hazards as terrorism and physical attacks on structures etc. have considerably increased over the past decade [1]. As such, the design and analysis of reinforced concrete (RC) structures under impact and blast loadings have been a major concern and are being studied by several researchers including some military divisions (TM 5-1300) [2]. In order to identify the most effective measures to achieve the desired level of protection against such impact loadings, numerous researches have been undertaken to develop impact-resistant materials and structures.

In addition to the brittle nature of concrete, its energy absorption capacity is rather poor which gives rise to the need of modifying it in some manner to improve its performance under such dynamic loads. The use of crumb rubber as a partial replacement of fine aggregates in concrete is such an alternative. Crushed scrap tires otherwise known as crumb rubbers (CR) are granules of rubber with the steel and fibers removed from them. Studies indicate that the use of CR in concrete reduces its compressive strength mainly due to the weak adhesion between rubber particles and the cement matrix. This eventually leads to a lower flexural strength of crumb

rubber concrete (CRC). However, higher toughness and impact strength than conventional concrete contribute to its efficacy for different structural and non-structural use ([3], [4], [5]).

About 4 billions of End-of-life tires (ELTs) are being disposed in landfills or are being stockpiled around the world [6]. This essentially consumes a lot of valuable space in landfills which serves as a breeding ground for harmful insects and pests. Moreover, it poses a serious threat of fire hazard. Importantly, the government of Canada has categorized waste tires as municipal solid waste which needs to be disposed of conforming to the provincial and municipal jurisdiction [7]. Therefore, recycling these scrap tires into useful value-added products can serve as a great benefit for both environment and economy of the country. Overall, utilizing CR as fine aggregates in concrete will contribute towards the production of environmentally friendly concrete or green concrete along with enhancing its performance under impact.

Another approach towards the production of sustainable green concrete is the addition of recycled concrete aggregate (RCA) as partial replacement of coarse aggregates (CA) in concrete. To elaborate, about 52% (by weight) of the 11 million tons of annual solid concrete and demolition waste (C&D) is held by concrete in Canada. Recycled concrete aggregate (RCA) can provide a sustainable solution by offsetting the increased demand on natural aggregates and by reducing carbon dioxide emission in the process of

manufacturing cement for new concrete production ([8], [9]).

Additionally, control of “carbon footprint” is a primary concern for the government of Canada. The province of British Columbia (BC) has earned international recognition for implementing effective measures towards the reduction of carbon footprint and thus acting as a leader in the green economy. BC mandate set legislated targets to reduce its carbon emissions by 33% by 2020 and 80% by 2050 [10]. Thus, researchers are focusing more on use of recycled materials in the construction industry to achieve this target. Utilizing recycled CR and RCA in concrete can provide an effective solution for material recovery and environmental hazards.

Studies show that the inclusion of RCA in concrete deteriorates its performance under impact to a certain extent [11]. However, a combination of CR and RCA can improve the impact resistance of recycled aggregate concrete (RAC) [12].

Several researches have been conducted till date on the effect of fiber incorporation in concrete to enhance its flexural behavior under impact ([13], [14], [15]). Fiber types studied include – steel, polypropylene, carbon, hybrid fibers etc. Results indicate satisfactory improvement in increment of flexural strength under impact. Especially, the post-cracking behavior of the fiber-reinforced specimens is noteworthy due to bridging effect of the fiber particles to resist propagation of cracking throughout. Also, it was effective in reduction of both the maximum and residual deflections under impact [13]. Importantly, the addition of fiber to rubberized concrete enhances the impact resistance of the concrete mix significantly [16].

This study presents a comprehensive review of the behavior of concrete under impact loading considering inclusion of rubber particles, RCA, and/or fiber in it.

2. Available methodology and test program

Determination of dynamic mechanical property of concrete as the impact resistance involves assessing its performance in terms of flexural strength under impact, energy absorption capacity, dynamic increase factor (DIF), and toughness index etc. Methodologies adopted vary among different researchers as there is a lack of established standardized impact test procedures. Thus, this section provides a brief review of the test procedures implemented in existing literature.

Previous studies [17] have shown that properties of concrete under the high-stress rates associated with impact loading could not be predicted only from the conventional static tests. Therefore, it is required to determine the flexural performance of concrete specimens under both - static and dynamic impact

loading to comprehend its material behavior.

Numerous researchers have performed experimental investigations on concrete specimens which includes drop-weight test method, which was adopted by a majority of them ([13], [14], [15], [16], [18], [19], and [20]). For instance, Taha et al. [19] used a drop hammer rig with a hammer weight of 10 kg and a drop height of 60 mm to conduct the impact test on 100 x 100 x 500 mm prismatic beam specimens. Whereas, Atahan et al. [21] employed an Instron Dynatup 8250 testing machine. The set up consisted of a block weighing 14.7 kg at the top of the chamber which when released was moving at a velocity of approximately 3.87 m/s imparting 109.8 J of impact energy on the specimens. In order to provide a comprehensive overview, the impact test set up adopted by Yoo et al. [15] is illustrated in Fig 1. To describe, a drop-weight impact test machine with a capacity of approximately 1200 J was used. The weight of the drop hammer used was 82 kg with variable drop heights of 180, 600, and 1400 mm imparting to three different potential energies of 145, 480, and 1130 J respectively according to the specimen sizes. All data - impact load, reaction load, and acceleration were recorded at a rate of 100 kHz through a dynamic data logger system. Moreover, a high-speed camera operated at a maximum rate of 2200 frames/s was used to investigate the cracking patterns of the specimens under applied impact loading [15]. Similar test setups were adopted in other studies [13], [18].

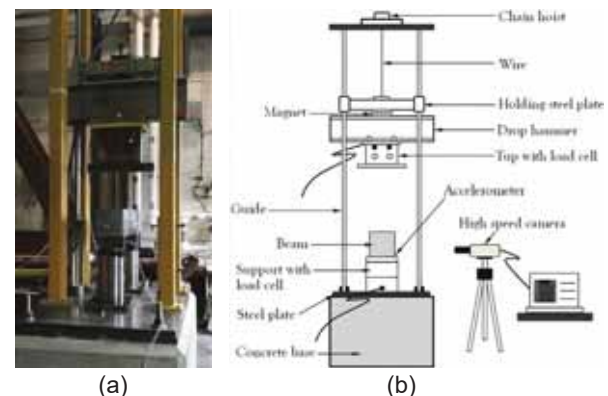


Fig 1: (a) Drop-weight impact test machine, and (b) Schematic diagram (Adopted from [15])

Moreover, Gao et al. [22] performed impact testing on fiber reinforced RAC specimens using stamp impact test method. Other methods adopted by few studies ([12], [23], and [24]) include the use of a split-Hopkinson pressure bar (SHPB).

In addition, a number of researches ([25], [26], [27], [28], [29], and [30]) have focused on assessing the performance of concrete under impact analytically. To elaborate, Abbas et al. [26] performed dynamic Non-linear Finite- Element Analysis (NLFEA) on wide reinforced concrete beams using FE analysis program

(ANSYS) under impact. Whereas, Behinaein et al. [29] considered steel-fiber-reinforced concrete (SFRC) beams under high-rate loading conditions and conducted NLFEA using the ABAQUS software.

Furthermore, both experimental and analytical methods were employed by few researchers ([24], [31], [32], [33], and [34]) in order to assess the performance of concrete under impact resistance. It provided more flexibility to analyze material behavior considering a higher number of variables.

3. Results and discussions

Impact resistance of rubberized concrete determined by previous studies including different variables considered are discussed in detail in this section.

Taha et al. [19] investigated the effects of incorporating chipped and crumbed tire rubber particles at four replacement levels (25, 50, 75, and 100%) by volume of the CA and FA respectively in concrete. Thus, they had a total of 9 different mixes including the control mix. Impact strength at 28 days of age was measured in term of impact energy (IE) i.e. the energy absorbed by the specimen up to the failure point. The span length considered was 400 mm for beam specimens sized 100 x 100 x 500 mm. Moreover, fracture toughness was also determined in terms of fracture energy, G_f using both notched and un-notched beams with a dimension of 100 x 75 x 350 mm having a loaded span length of 300 mm.

Results showed that the impact strength of the specimens significantly improved with an increment of rubber replacement in concrete. However, it started to decrease beyond a replacement level of 50% for both chipped and crumbed tire particles.

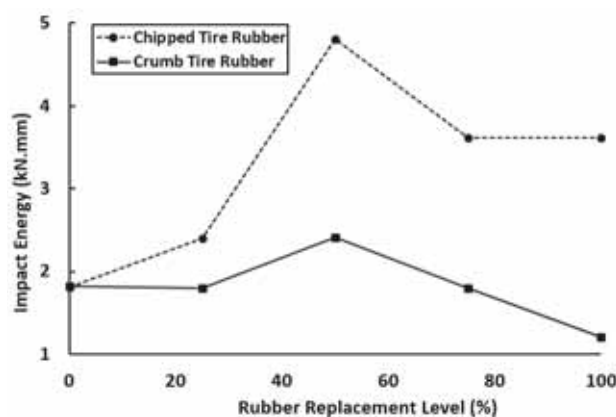


Fig 2: Effect of aggregate replacement ratio on the impact energy of rubberized concrete [19].

Fig 2 [19] illustrates the trend of IE change with an increase of replacement levels of the rubber particles. The improved energy absorption capacity of

rubberized concrete up to a medium replacement level (50%) can be attributed to the low stiffness of rubber particles allowing the rubber-cement composite to have a relatively higher flexibility and thereby, higher energy absorption capacity. However, the rubber-cement composite performs weaker due to the high strains generated under loading when the replacement level of rubber is increased to a very high level [19] [35]. In addition, Taha et al. [19] found a higher value of fracture energy for rubberized concrete containing 25% chipped tires than the conventional concrete. Overall, they determined the optimum tire rubber replacement level as 25-50% considering the combined effect of compressive strength and flexure toughness.

A similar study was performed by Atahan et al. [21] where CA and FA were replaced by coarse and fine crumb rubber simultaneously at five replacement levels (20, 40, 60, 80, and 100%) totaling to six different mixes including the control mix. They assessed the potential of using rubber particles in concrete safety barriers which are prone to very high impact loads. For this purpose, they tested eighteen 10 cm x 20 cm cylinders under dynamic drop test. Consequently, the energy absorbed by the specimen was calculated from the integral of the load vs. time curve generated from the Dynatup data logger system [21]. Results show that the load carrying capacity and the energy dissipated at the maximum load decreased and increased respectively with increment of rubber replacement levels in concrete. To specify, a decrement of 71.6% in the maximum load and an increment of 160.8% in the energy dissipated at maximum load between the control specimens and the 100% rubber replacement specimens, respectively was obtained. To summarize, the optimum replacement level was found as 20-40% for maintaining desired concrete strength with excellent energy absorption capacity. Whereas, up to 60% level of replacement can be employed when considered for use in non-structural high impact zone applications as highway barriers [21].

A slightly different approach was adopted by Al-Tayeb et al. [33] where they performed three-point impact bending test on a hybrid concrete consisting of a double layer beam sized 50mm x 100mm x 400 mm with rubberized top and normal bottom. Two levels - 10 and 20% of volumetric replacement of sand by fine rubber crumb were considered in this study. Moreover, the dynamic behavior of these hybrid specimens was also analyzed numerically using the finite-element method (FEM) based on LUSAS V.14 software. It was found that the impact ultimate bending load capacity increased with increment in CR replacement levels for the hybrid beam which is illustrated in the in the load-deflection curves obtained from the impact tests. However, the static peak bending load decreased for the same. Moreover, fracture energy was calculated as the area under impact bending load vs. displacement curve similar to

Banthia et al. [18]. Consequently, increase in fracture energy by 194% and 268% were obtained for sand replacement by fine CR at levels of 10% and 20%

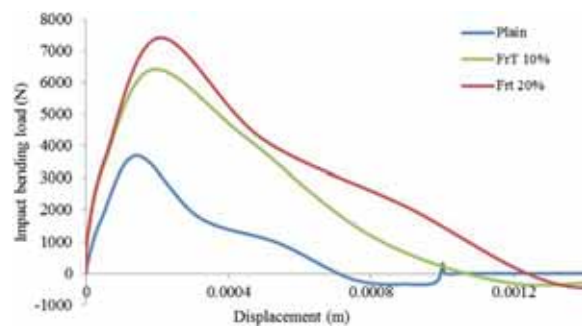


Fig 3: Impact bending load against deflection for hybrid concrete specimens (Adopted from [33]).

respectively (Fig 3). Results found were similar to the previous studies ([19], [21]). In addition, the use of hybrid concrete helped to develop concrete having an enhanced impact strength along with better tensile capacity by employing rubberized concrete with a higher energy absorption capacity as the top layer and placing the conventional concrete with better tensile capacity as the bottom layer [33]. Furthermore, the experimental results were validated analytically by developing a FEM model in LUSAS V.14 software.

A similar trend of improvement of impact strength with increment of rubber content for rubberized concrete was found in several studies ([36], [37], [38]).

However, Liu et al. [23] found a decrease in peak stress under impact with the increment of rubber content in contrary to other studies. The study [23] considered four levels of CR replacement up to 20% with an increment of 5% to determine the influence of rubber content on crumb rubber concrete (CRC) under repeated impact using a split-Hopkinson pressure bar (SHPB). CRC performance under impact was assessed in terms of peak stress, strain rate, and energy absorption capacities measured from the area under stress-strain curves. Although the peak stress was reduced, both peak and ultimate strains were increased with an increment of CR content. Also, higher energy absorption capacities were obtained for CRC than conventional concrete. On the whole, the CRC mix with a CR content of 10% experienced the least damage among all the mixes with satisfactory compressive strength. Fig 4 (a) and (b) shows the stress-strain curves under repeated impact for normal concrete (NC) and CRC-10 with a CR level of 10% as obtained by Liu et al. [23].

Another study by Liu et al. [24] considered a combination of CR and steel fiber to improve the energy absorption capacity of conventional concrete. Precisely, the influence of strain rates, rubber sizes, and rubber content on the on the impact resistance of rubber reinforced concrete (RRC) and steel fiber

reinforced concrete (SFRC) were investigated for 17 different mixes in terms of strain rates, dynamic compressive strength, dynamic increase factor (DIF) – ratio between peak stress under impact and static loading, toughness index or the energy absorption capacity in terms of area under stress-strain curves similar to [23]. Results show that energy absorption capacity of RRC increased up to a CR replacement level of 10% beyond which it started to decrease. However, it was higher than that of NC at all levels. Importantly, SFRC with an addition of 0.5% steel fiber into RRC significantly improved the dynamic compressive strength and the DIF than RRC. Moreover, an improved Holmquist-Johnson-Cook dynamic model with 10 modified material parameters was developed and the failure modes of specimens under high strain rates were analyzed by numerical simulation using the finite element software ANSYS/LS-DYNA [24].

Performance of rubberized concrete incorporating RCA in it, waste-rubber-modified recycled –aggregate concrete (RMRAC) in other words, under impact has been experimentally investigated by Li et al. [12].

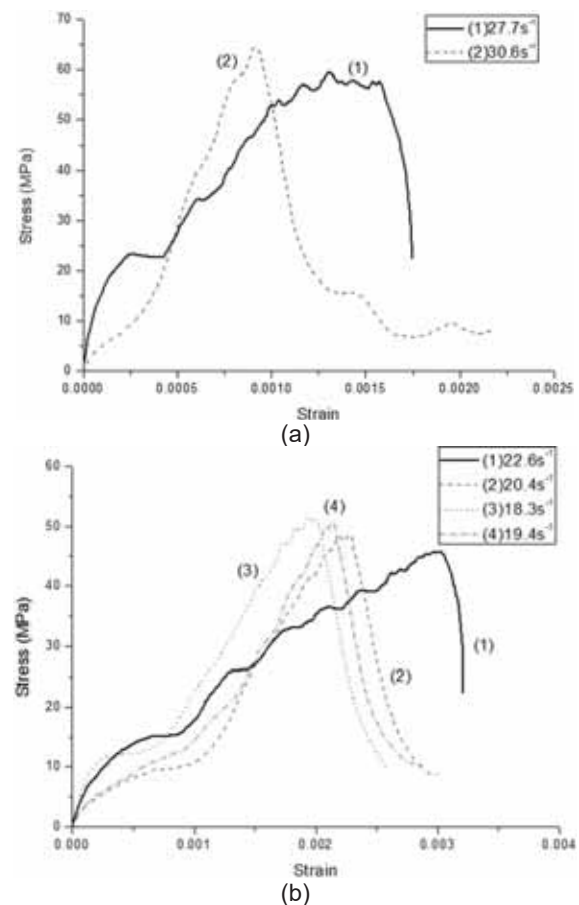


Fig 4: Stress-strain curves of (a) NC and (b) CRC-10 (10% CR) under different impact times (Adopted from [23]).

Dynamic mechanical properties were measured in similar terms as [24] using the similar test set up using a SHPB. It was found that RMRAC had better energy absorption capacity than RAC. For instance, the peak stress values were significantly decreased for RMRAC specimens (Fig 5 [12]) than RAC specimens under impact loading. This was attributed to the better energy absorption capacity of rubber due to friction between rubber and concrete than that of aggregates in RAC [12]. Also, RMRAC had higher toughness index than all the RAC mixes due to the incorporation of rubber granules in it. However, it was decreased slightly due to increase in rubber particle size. Overall, the study [12] recommends use of RMRAC with a rubber content of 10% with particles size higher than 0.864 mm as an environmentally friendly material for use in pavements.

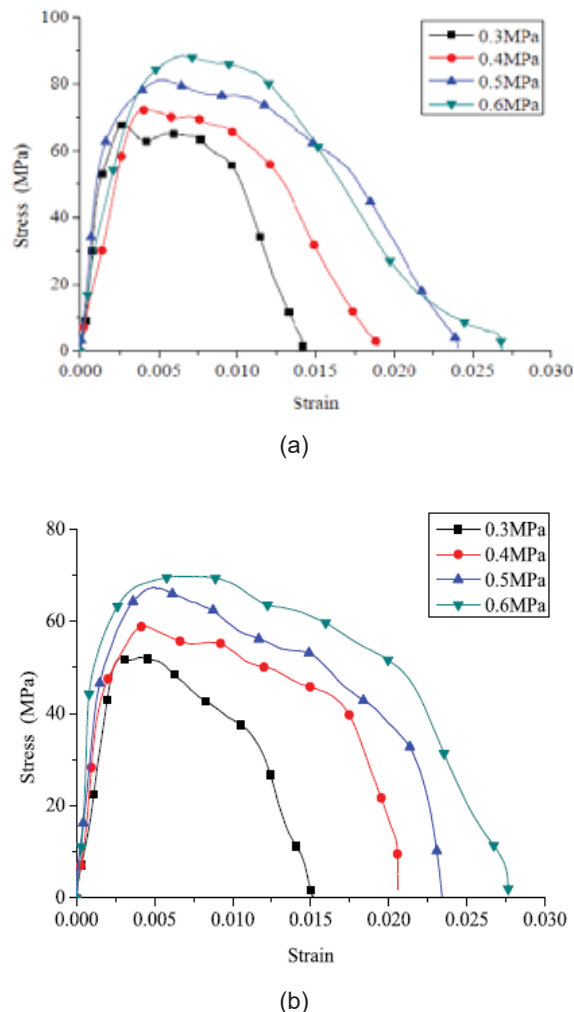


Fig 5: Stress-strain curves of (a) RAC and (b) RMRAC-0.864-10% under different input pressures (Adopted from [12]).

Moreover, previous studies ([22], [11]) have found RAC to have lower energy absorption capacity than conventional concrete under impact. However, addition of fiber has been found to have positive effects on the impact resistance of RAC [22]. Therefore, modification of RAC by incorporating CR or fiber or a combination of both can prove to be an efficient construction material with enhanced performance under dynamic loads as impact. However, very limited number of studies have focused on investigating the impact performance of this new material.

Few researchers have focused on the use of different types of fiber in addition to CR in concrete. For instance, Noaman et al. [16] have incorporated hooked-end steel fiber with a volume fraction of 0.5% in combinations with two different ratios (17.5% and 20%) of CR by volume in concrete. They found impact energy at ultimate loads to be higher by 84% and 108% for rubberized mixes with 17.5% and 20% CR replacement levels respectively. Importantly, Impact energy at the ultimate or final crack was 52% and 61% higher for rubberized steel fiber concrete than for the steel fiber mix (Fig 6). The inclusion of hooked end steel fibers resulted in improved bonding under cracking and a better redistribution of cracks under impact loads. This resulted in a positive synergy between the rubber particles and the steel fibers in the mix leading to much higher energy absorption capacity of the concrete mix [16].

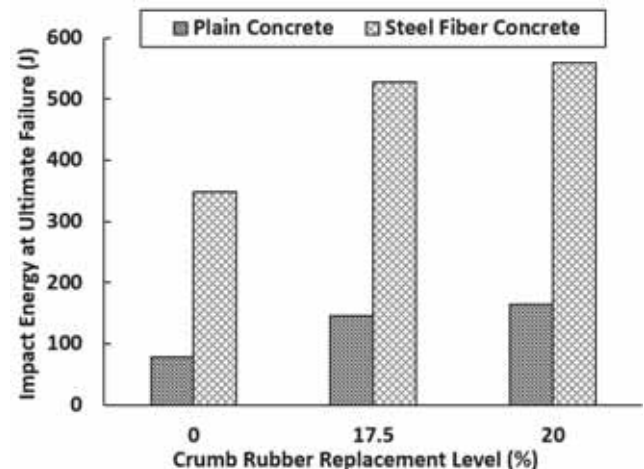


Fig 6: Impact energy of steel fiber reinforced rubberized concrete at ultimate failure [16].

Although a number of studies have been conducted to determine the performance of concrete under impact numerically, studies on numerical investigation of impact resistance of rubberized concrete is very limited till date ([25], [26], [27], [28], [29], and [30]).

4. Conclusions and outlook

On the whole, the integration of recycled rubber particles and recycled coarse aggregates as partial replacement of fine aggregates and natural coarse aggregates respectively in concrete can contribute substantially towards the production of green concrete and can provide a viable solution to address the harmful environmental effects of solid waste disposal. Based on the results obtained from previous studies, it can be concluded that the inclusion of recycled waste rubber particles as partial replacements of aggregates - both coarse and fine, enhance the energy absorption capacity or the impact resistance of concrete. Nevertheless, the optimum replacement level of CR varies depending on the intended use of the rubberized concrete. Importantly, the inclusion of RCA to rubberized concrete can result in improved impact resistance of concrete than RAC. Moreover, enhanced toughness can be obtained by the addition of fiber to rubberized concrete.

However, only a few studies have been conducted to date investigating on the impact resistance of rubberized concrete containing RCA and/or fiber. Hence, further in-depth research on this new material would significantly add to the literature and facilitate the production and implementation of this sustainable green concrete.

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Thermal performance of double and triple glazed windows: Experimental results from lab and in-situ measurements

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Abstract:

New residential buildings are not only larger in size but also have higher window to wall ratios which results in higher heat losses. In order to decrease the heat losses associated with glass windows, several types of window technologies have been developed. Double and triple glazed windows with argon filled coatings are two of the most common types of window systems that are being used in green residential buildings. This study assesses the effective thermal performance associated with typical double and triple pane Low-E argon filled glazing window systems. The two types of windows were tested for their thermal performance through laboratory and field testing. An experimental setup similar to Hot Box apparatus was used to measure the temperature variation of window glass panes in a controlled environment. The field values were collected from two similar residential houses present in Kelowna, BC (Canada). One house had double glazed windows and the other house had triple glazed windows. Variation in temperature profiles during three days of summer and three days of winter showed the thermal performance during these times. Laboratory measurements showed results similar to window thermal performance for winter days. The thermal performance evaluated in this study can be used to update building energy model calculations of houses and hence attain more realistic energy simulation results.

Keywords:

Advanced window glazing, Thermal performance, Low-E, Testing, Measurement.

1. Introduction

Depleting natural resources, waste accumulation, global warming and other environmental problems have prompted actions to reduce the energy use in buildings and obtain a sustainable environment. New and innovative technologies are being developed to make the current and newer buildings energy efficient. The energy consumption of building sector has surpassed industrial and transportation sector and accounts for 40% of total primary energy [1]. The Government of Canada has set its target to reduce the energy related greenhouse gas reductions to levels 30% below those in 2005 [2]. In this regard, the government of British Columbia, has also stepped up its efforts to meet 2032 challenge of achieving net-zero energy buildings [3]. In this regard an energy step code has been proposed for easier transition to achieve 2032 target. Improvement of building envelope is the first step in this energy step code which will take buildings from current building code an upper enhanced compliance level.

Building envelope is an important component of the house that if not properly designed can result in high heat losses in winter and also higher heat gains in summer resulting in use of extra energy and increase of carbon footprint of the residential buildings. The energy impact of building envelope depends upon the thermal inertia and thermal transmittance values of its components [4]. The heat gains and losses by a house envelope increase with the percentage increase of wall area taken up by windows. Compared to other envelope components of the house, typical

windows have low thermal performance which result in high heat loss during winter season i.e. higher heating costs and high heat gains during summer: i.e. greater cooling costs. Replacement of traditional single pane windows with Energy Star® rated windows can save up to 8% on our energy bills [5]. Similarly by use of energy efficient windows decrease in green gas houses is observed [6]. Windows are transparent components of a house envelope that also play an important part in our interaction with outdoor environment. They enhance the aesthetic appearance of the building structure and supply sunlight into the household[7].

Window performance is determined by three key properties: Thermal transmittance (U-value or 1/R), solar transmittance (SHGC) as well as air tightness of windows are important parameters that effect the thermal performance of windows [8]. In addition, location of building, building orientation, local climatic conditions and building design parameters also affect how windows with different type of glazing will perform [8].

U-value of window glazing's is used to evaluate the amount of heat flow between inside and outdoor environment of a building [9]. The amount of heat flow in window glass depends upon the degree of temperature difference between the two sides of glass. U-value for vacuum type glazing was experimentally tested by Simko et. al (1999); using two different methods, a small area guarded hot plate and a guarded Hot Box method to determine heat

flow in glazing [10]. The heat flow (Q) can be calculated with Eq. 1.

$$Q_{window} = U.A.(T_H - T_C) \text{-----}(Eq. 1)$$

Where

- U = Effective Thermal Transmittance (W/(m² K)
- A = Surface area of the window (m²)
- T_H = Temperature of hot side of glazing (°C)
- T_C = Temperature of cold side of glazing (°C)

Low-E windows are characterized by glass coated with special metal coating that is capable of reflecting or retaining heat and light on one side of glass [8],[9]. Use of more than one glass pane in window can help in reducing U-value as desired [13]. Multi-pane Low-E windows prevent indoor heat losses, along with providing a good sound barrier to outside noise. Albeit these advantages widespread use of Low-E windows is hampered by their higher costs than ordinary windows [14].

Research by Menzies & Wherrett (2005) evaluated the energy and costs savings associated with the installation of different types of double and triple pane Low-E windows and concluded that if specifications of windows are optimized significant savings are possible [15]. Asurdubli et al. (2011) found approximate thermal transmittance value on aluminum framed windows and compared values for European; the American; and the Russian standards. Their study showed that Hot Box test standards which indicated in both ASTM C1199-09 and EN ISO 12567-1 give 3% higher U-values than Russian GOST 26602.1-99 standards [16]. Gasparella et al. (2011) performed analysis to evaluate critical parameters in window design[17]. Double and triple glazed windows were tested for change in building energy use considering different window sizes, building orientation and location. It was seen that large glazing's can result in higher energy savings and south orientation is the best performing side for using these windows[17]. Some studies have been focused on newer window technologies and their related advantages [14]. The review studies performed by Jelle et al. (2012) and Rezaei et al. (2017) address conventional, advanced as well smart windows technologies available today [12], [13]. Recently, Cuce et al. (2017) performed an experimental study on air- tightness and the energy loss associated with double glazed argon filled windows [18].

Main objective of this study is to perform a preliminary analysis on thermal performance of two types of windows that are locally available for the single family detached residents of Kelowna, Canada. In-situ testing from two model homes in Kelowna and hot-box test in the University of British Columbia, Okanagan Campus (UBC-O) laboratory are

performed to gather temperature data on hot and cold sides of the window panes. The study will be helpful in filling the energy efficiency gaps between the predicted and actual energy use of residential buildings.

2. Methodology

This research aims to investigate the thermal performance of double and triple pane argon filled Low-E windows. The research takes into account temperature measurements from in-situ tests that are carried in actual houses as well as laboratory experiment similar to Hot Box test. The methodology for this study is provided in Fig 1. More details of the windows tested are shown in Table 1. It can be seen from this table that TG2 used has better thermal transmittance and Solar Heat Gain Coefficient values than DG1. If all the other factors are kept constant the TG2 should show better thermal performance as compared to DG1.

Table 1: Type of Window Tested

Window	DG1	TG2
Description	Vinyl double glazed windows c/w single 180 Low-E	Vinyl triple glazed windows c/w double 366 Low-E
Illustration		
R-Value (at Centre of Glass)	3.85	8.33
Solar Heat Gain Coefficient	68	24
Ultraviolet Transmission	29	1
Visible Light Transmission	79	47

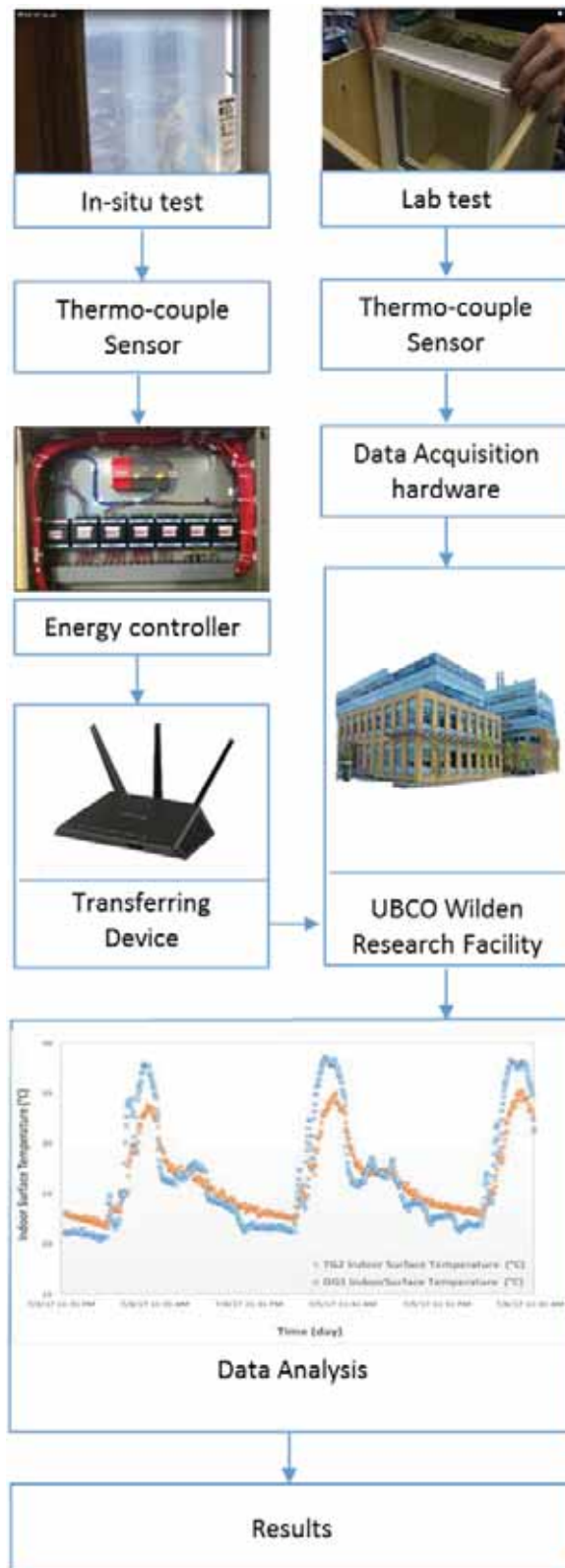


Fig 1: Research Methodology

The research is carried in two main parts: In-situ and laboratory testing. The in-situ and laboratory tests were performed on typical double and triple pane windows for both in-situ and laboratory tests. Windows used in real houses and window tests specimens for laboratory were all by the same manufacturer.

2.1 In-Situ Data Test

Two houses the “Home of Today (HOD)” installed with double pane Low-E windows (DG1) and the “Home of Tomorrow (HOM)” installed with triple pane argon filled Low-E windows (TG2) were used for the in-situ measurements. Both these houses are part of “Wilden Living Lab Project” in Kelowna ,BC (Canada) [19]. The houses are located side-by-side and have similar floor plans. Since both houses are subject to same weather the data collected from these can be used for comparative study of TG2 and DG1. Temperature measurements are made from two test windows, located on south facing walls of these houses and hence are both exposed to maximum amount of sunlight throughout the year.

The temperature data was collected from the two windows from January 2017 to October 2017 and showed the window performance under the Kelowna weather conditions. For the current study temperature data for 3 days of Summer (4-6 July) and 3 days of winter (31 –Oct to 2-Nov) were analyzed. Weather data files show the average temperature for July, 2017 was 21°C and winter data was of Canada show on average highest temperature of 18.8°C are observed during month of July while normal average temperature of 15.5°C was seen during October 2017 [20].

K-Type thermocouples were attached on the glass surfaces of each window. The temperature data collected from the outermost glass pane was called “Outside Surface Temperature” and the temperature collected from the surface of glass facing inside of the house was called “Indoor Surface Temperature”. The data from thermocouples was transferred by means of energy data collectors that by means of network connection transferred data to Wilden Research Facility located at UBC-O. The temperatures of the two sides were measured every 5 minutes.

The data collected in UBC-O Wilden Living Lab Research Computer was viewed with Niagara Workbench 4.2 tool[21]. This tool offers a friendly user interface where data from the in-situ tests can be visualized and necessary changes needed to increase building energy efficiency can be easily identified. The data from Naigara workbench was analyzed in Microsoft excel and the results are explained in Section 3.

2.2 Hot Box Test

The amount of heat flow from a window can be calculated by the Hot Box Test [16]. For this research a small scale test apparatus similar to commercial Hot Box was produced in the School of Engineering, UBC-O (Fig 2).

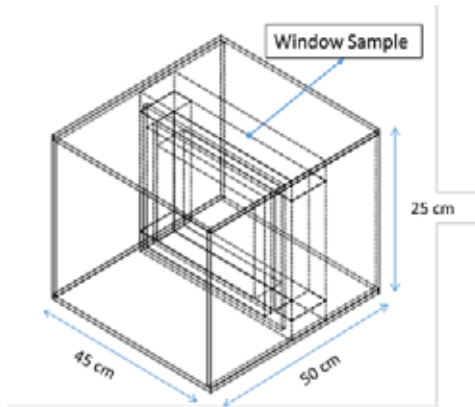


Fig 2: Hot Box Test Apparatus

The box was constructed of plywood board, well insulated with 2-inch thick styrofoam on inner sides of the box and edges of window test unit, to attain the measurement of approximate heat transferred in the window sections tested. The dimensions of the test box were 50 cm x 45 cm x 25 cm and is divided into to equal sections. Manufacturer provided small size window sections were placed in the middle of Hot Box apparatus. Thermocouples were mounted on glass surface on both side of window section and a commercial data acquisition system Agilent IO was used for data collection from the test box. Agilent IO Libraries suite contains a number of libraries and utility programs that can be used for data communication among different instruments [22].

A heating source was provided on one side of the glass to check for heat transfer. The temperature collector from glass surface facing heating source directly was called "Hot Side Temperature" and the temperature collected from outermost pane not facing heating source was called "Cold Side Temperature". The Hot Box tests were performed in November 2016. The temperatures of the two sides were measured every 10 seconds.

3. Results and Discussions

3.1 In-situ Test Results

Large amount of temperature data was collected from in-situ testing. For this preliminary study we analyzed data for three warm summer days (03-July-2017 to 06-July-2017) and three cold days (30-October-2017 to 02-November-2017). Indoor temperature data for two types of windows for winter is shown in Fig 3

while indoor temperature data measured for summer is shown in Fig 4.

It is seen that during winter the indoor temperature of room with TG2 windows had remained warmer as compared to DG1. For summer data the indoor temperature of TG2 remained lower during peak times while were approximately similar on other times of the day.

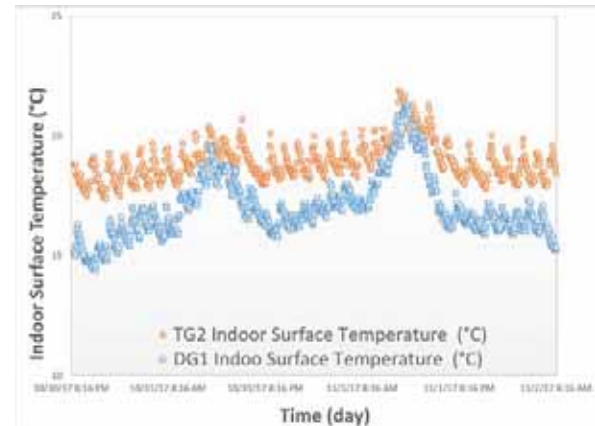


Fig 3: Indoor Temperature Variation (Winter)

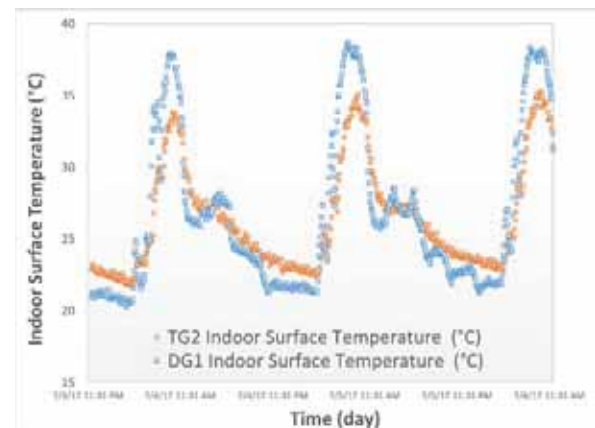


Fig 4: Indoor Temperature Variation (Summer)

A comparison between double and triple glazed windows temperatures with respect to outdoor temperature is illustrated in Fig 5. The average values of indoor temperature for double and triple glazed windows from the data are 17°C and 18.9°C respectively. We also know from the manufactures data that U-values of TG2 is more than DG1 window glass. Analysis of three days of winter data shows that the indoor temperatures for both DG1 and TG2 are positively correlated with outdoor temperatures. In addition, the indoor temperatures for DG1 are more strongly correlated with the Pearson's correlation coefficient value as 0.9 as compared to TG2 where this value is 0.74. This shows that more heat is being lost in DG1 as compared to TG2. It is also observed

as outdoor temperatures are increasing, the difference in indoor temperatures decrease. This may imply that TG2 thermal performance is better at lower temperatures and with the increase of outdoors temperature both DG1 and TG2 will start to behave similar way.

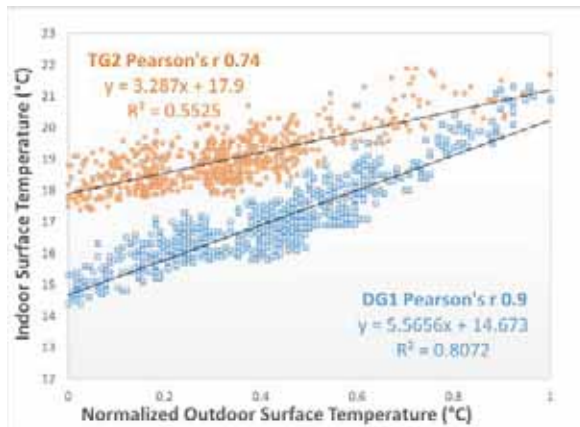


Fig 5: Correlation Diagram (Winter In-situ Data)

Fig 6 show the temperature variation for two type of windows observed during three typical summer days in July. It is seen that unlike winter data the correlation values between outdoor and indoor temperature for the two window types TG2 and DG1 are very similar. The relationship between inside and outside pane temperatures is still linear.

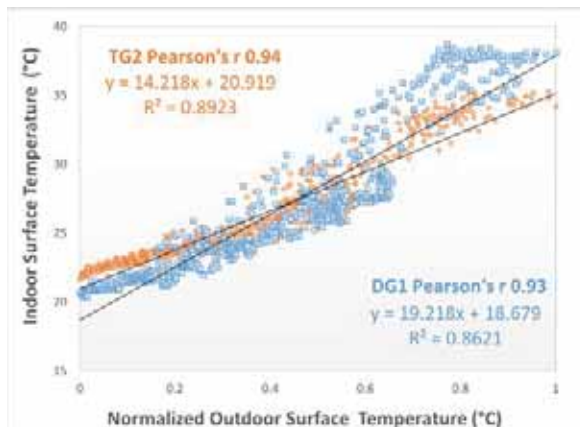


Fig 6: Correlation Diagram (Summer In-situ Data)

3.2 Laboratory Test results

The Hot Box test is performed for checking heat loss from a glass and hence, TG2 and DG1 samples tested in laboratory should show similar behavior as winter data collected for in-situ test. The temperature data collected through Agilent data acquisition system was analyzed in Microsoft excel and the results are shown in Fig 7. It is seen that even though the duration of lab test was short the temperatures on hot

and cold side of tested windows are more correlated for DG1 as compared to TG2. However, one key difference as compared to field test data is the relationships between cold and hot faces of window glass are showing a non-linear relationship.

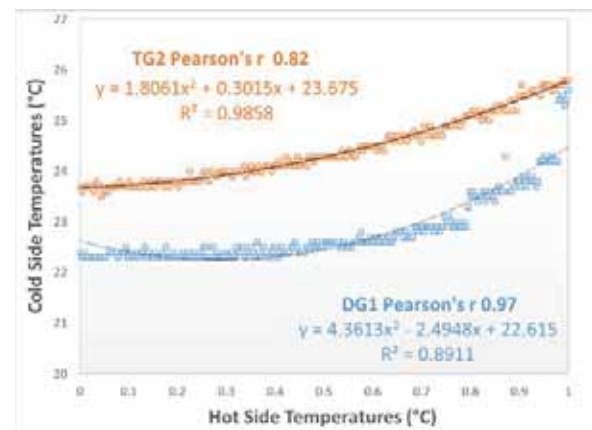


Fig 7: Correlation Diagram (Laboratory Data)

3.3 Limitations

The study is limited to effect of double and triple glazed windows on energy use in residential buildings. This research analyzes a limited set of data and errors are possible both in data collected on site and in laboratory. In addition, measurement of heat flux variation over time was not observed which have helped in calculation of actual energy consumption needed.

4. Conclusions

Energy efficient window technologies can help on having energy bills and reduce the carbon footprint of residential buildings. This study tested the performance of double and triple glazed window based on data collected through in-situ test and laboratory hot-box tests. Field data for three warm summer days (03-July-2017 to 06-July-2017) and three cold days (30-October-2017 to 02-November-2017). The in-situ test results showed that winter performance for triple glazed Low-E glass was better than double glazed Low-E glass. This proves, that more savings in heating energy loads are possible through triple glazed Low-E windows. In Summer, however, the correlation values between temperatures of inside and outside face of house windows for triple and double glazed windows were found to be almost similar. The laboratory experiment performed in (November-2016) showed similar results to data collected from 3 days in Winter. However, the relationships for in-situ and laboratory data are different. The laboratory data showed a non-linear distribution while site data showed a linear variations

of internal and external temperatures with passage of time.

Next step of this research will be to perform a detailed study on temperature measurements over a span of whole year from in-situ data to evaluate the optimal energy savings possible. Life cycle assessment will also be conducted along with Life cycle costs study to determine the most suitable window system for residential buildings.

Detailed simulations considering other relevant of parameters such as glass surface humidity, type of coatings, type of air gap and filling, window frame material as well as actual air tightness of these windows that need to be tested. More studies are also needed in order to determine the type of windows needed to maintain comfortable indoors with minimum use of energy and cost. In this regard an optimization study for selection of window types for a building needs to be performed. Window optimization model would be based on environmental, economic as well as social parameters.

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Measuring Dynamic Thermal Resistance of Building Envelope Assemblies

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Abstract:

Thermal resistance of complex building assemblies is presently evaluated through simulation models using vendor published R-values of the various building components. Calculated R-values seldom take into account variations in construction, deterioration of assembly components over time and assemblies consisting of multiple components such as window frames, studs, fasteners, inconsistent insulation, deficiencies in the installation, variable air gaps and thermal bridging. The Building Envelope and Technology Access Centre (BETAC) and SMT Research have installed a large network of sensors embedded throughout the new Skilled Trades and Technology Centre (STTC) located on the Red River College, Notre Dame Campus in Winnipeg, as well as a 32-storey high-rise building located at 360 Main Street in downtown Winnipeg, Manitoba. Several different exterior assembly types have been instrumented throughout the building envelope, as well as the roof and green roof assemblies. The sensor set installed throughout the building consists of heat flux sensors embedded inside specific assemblies alongside temperature sensors positioned across the insulation material. The Dynamic Thermal Resistance can be calculated from the installed sensors and compared to simulated models in order to validate both the monitoring methodology as well as the accuracy of the simulation. The analysis will be performed in real-time during normal building occupancy of the building influenced by the temperature extremes inherent to Winnipeg. Results will be compared and analyzed with respect to external climatic influences as well as an analysis of convective air currents within the wall cavities. This paper will demonstrate the methodology and sensor set required to obtain the required quantitative data in both instrumented buildings. Monitored results from the downtown building will be analyzed and compared against calculated values and model simulations.

Keywords:

Dynamic Thermal Resistance (DTR), Heat Flux, Effective R-value, Monitoring, Modelling, Sensor, Living-lab, Temperature extremes

1. Introduction

This paper covers the methodology and sensor instrumentation required to measure and analyze the Dynamic Thermal Resistance (DTR) of a building. This study addresses two different buildings located in Winnipeg, MB. Both buildings are subjected to a wide range of environmental conditions; seasonal temperature fluctuations from -40°C to +40°C, wind gusts in excess of 100 km/h, torrential rain events and winter blizzard conditions make this geographic location ideal for thermal analysis and performance testing.

The STTC building is a 9300m² (100,00ft²) new construction, two-storey multi-purpose educational building used as laboratory and shop space. It will serve as the educational facility used to train and educate students enrolled in RRC's Construction Trades Programs. The building will also serve as an educational tool to all faculty members, providing real time, accessible data from its network of embedded sensors. Seven different exterior wall types are instrumented including six varying opaque wall assemblies and one curtain wall. Also instrumented, are the two varying roof types, including the green-roof assembly. The sensor installation is complete, however the building is not in a controlled state as it is still presently under construction. Once occupied, the

building will serve as a 'living lab' where the data and analysis will be discussed in future papers.

The existing 32-storey high-rise, 56,000m² (600,000ft²) office building located at 360 Main Street in downtown Winnipeg underwent a major renovation with a complete replacement of its exterior wall façade with a new spandrel panel system. Sensors were embedded in the new façade on one floor and several months of data is presented and discussed in this paper.

In late 2013, Manitoba adopted The National Energy Code for Buildings (NECB) and began enforcement in December 2014. The NECB sets the minimum acceptable standards for building performance of new construction and those undergoing major renovations, as related to energy use. Part 3-*Building Envelope* of NECB 2015 details the minimum thermal transmittance characteristics of building envelope assemblies. Achieving targets is accomplished by following one of three Compliance Path methods. (National Energy Code for Buildings, 2015).

1. The Prescriptive Path stipulates a building component or assembly type to be built to a certain minimum R or U-Value.
2. The Trade-Off Path allows for an assembly type or component of lower R-Value to be used when a similar, corresponding assembly type or component has a higher R-Value, all whilst

maintaining the minimum prescriptive performance levels.

3. The Performance Path requires the proposed building be modeled using specified computer software, and shows the proposed design of the building performs better than that of a similar referenced building.

All three Compliance Paths and modeled methods require calculations and inputs such as the building geometry, size, as well as knowledge of specific building components with known R-values. All methods take into account varying aspects of the thermal bridging occurring through the assemblies, however, they do not take into account the variations in construction, inconsistent insulation and materials, variable air gaps or the deterioration of assembly components over time (Modera, M. P., Sherman, M. H., and Sonderegger, R. C., 1985). The major contribution of this study is to design a system capable of measuring heat flux over a large surface area in order to encompass a variable complex assembly. The heat flux in conjunction with the change in temperature across the assembly provides the in-situ effective R-value or *Dynamic Thermal Resistance* of the wall assembly.

The impact of this study is to establish a quantitative metric to benchmark the energy efficiency of pre-existing assemblies and materials. This will allow unique materials, assemblies and construction techniques to produce a quantitative measurement that can be recorded and monitored. Energy savings will be achieved by maintaining optimal thermal efficiency over time as the monitored wall structures will essentially be subject to continuous real-time commissioning.

2. Sensor Installation Plan - RRC STTC

Installed throughout the building, on seven different exterior wall types and roofing assemblies, are a network of moisture and thermal sensors.



Figure 1. Red River College's Skilled Trade and Technology Centre (Photo Credit RRC)

Green Roof Performance Monitoring

Moisture Detection Sensors are installed in a dense 1.5m (5ft) grid pattern within the green roof assembly. In addition to moisture detection sensors located under the roofing membrane itself, the thermal resistance of the roof is instrumented with heat flux sensors on the underside of the roof, along with temperature sensors on both the bottom and top portions of the assembly.

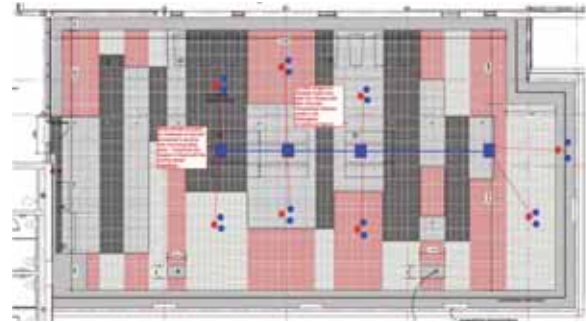


Figure 2. Green roof heat flux and temperature sensor locations.

Building Envelope Sensor Installation

The STTC building has sensors embedded within six different exterior opaque wall types, including variations of masonry and metal siding. Also instrumented are vision walls, including windows and the curtain wall assembly. The type of sensor and placement is dependent on the wall, elevation type and mounting assembly. Moisture Detection Sensor (MDS) tape was placed in areas susceptible to moisture intrusion. Point Moisture Monitoring (PMM) sensors were placed in the plywood mounts for the curtain walls, and a combination of heat flux and temperature sensors were placed around the specific assemblies and insulation types to measure thermal efficiency and thermal resistance. A typical sensor installation with temperature, heat flux and differential pressure is shown in Figure 3 and Figure 4. Differential pressure sensors were installed to observe the airflow magnitude and direction across the various building envelope assemblies.



Figure 3. Interior Heat Flux Sensor Installation



Figure 4. External Heat Flux, Temperature and Pressure Installation

3. Sensor Installation Plan – 360 Main Street

Heat flux and temperature sensors were installed on the 13th floor of the 32-storey building located in Winnipeg's downtown. The building has 12 different wall facings; however, six varying orientations were selected to be instrumented, to provide a representative sample of the buildings perimeter.



Figure 5. 32-Storey High-Rise Building

Sensors were positioned at the ceiling level to avoid the space heating equipment, as the heaters would have an influence on the heat flux sensor readings. In addition, the location allows the data loggers to be connected without any wires or cables to be visible within the space. The sensor location layout is shown in Figure 6.

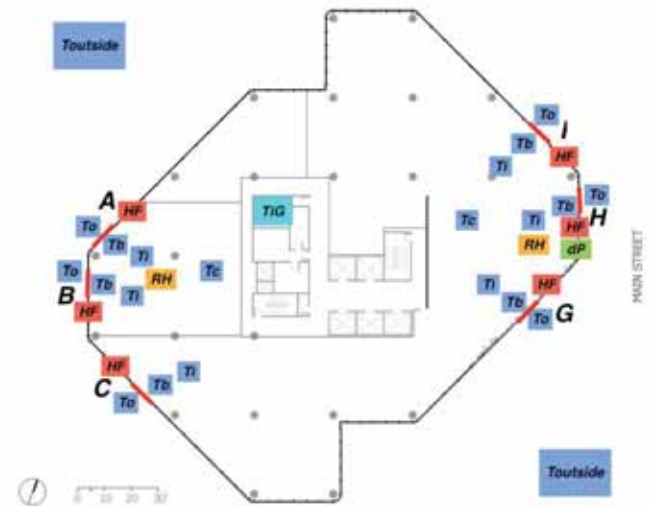


Figure 6. Sensor Locations

Identification Labels	
To	Temperature outside of back pan insulation
Tb	Temperature located on inside of back pan
Ti	Temperature 10 cm away from back pan inside airspace
Tc	Ambient room temperature
HF	Heat Flux Sensor
RH	Relative Humidity sensor located in A3
dP	Differential Pressure
TiG	Wireless Gateway
Toutside	Outdoor temperature from a local weather station was used.

Sensors installed around the spandrel panel of the curtain wall assembly are shown in Figure 7. Temperature sensors are installed between the back pan and exterior curtain wall (To) as well as on the interior back pan (Tb) and 10cm (4 inches) off the interior back pan (Ti). The exterior ambient temperature (Toutside) and the interior room temperature (Tc) are used to calculate the temperature across the entire assembly. The Dynamic Thermal Resistance is calculated using the external temperature (Toutside) and the interior ambient temperature (Tc). The heat flux is measured using a PHFS-09e FluxTeq heat flux sensor as shown in Figure 8.

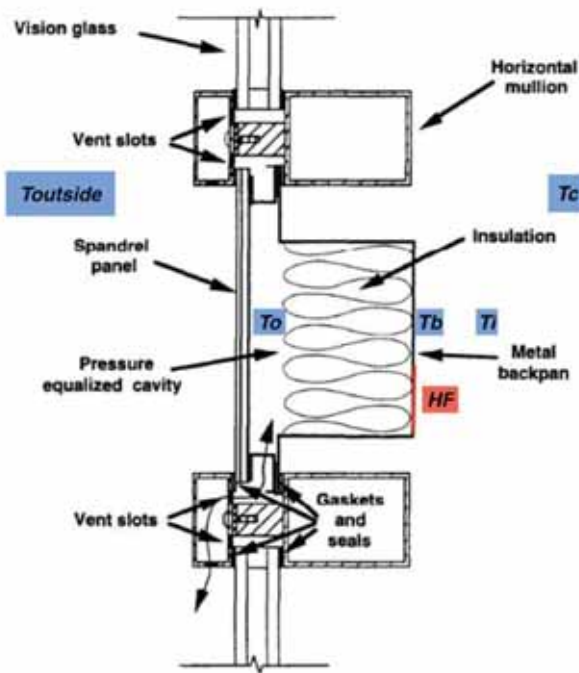


Figure 7. Sensors across back pan

Dynamic Thermal Resistance (DTR) is calculated using the standard R-value formula. Results are expressed in R-value (US) units.

$$RSI = \frac{\Delta T}{\text{Heat Flux}} = \frac{T_{\text{outside}} - T_{\text{inside}}}{W/m^2}$$

$$DTR = RSI \times 5.678263337$$

The locations of the sensors on the materials are shown in Figure 8 and Figure 9. Tc was used as the internal sensor to avoid any back pan radiant temperatures.

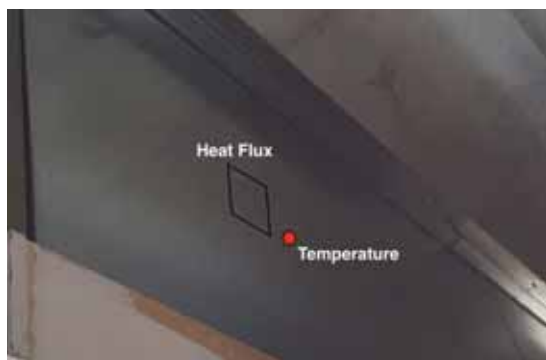


Figure 8. Internal Temperature (Ti) sensor location

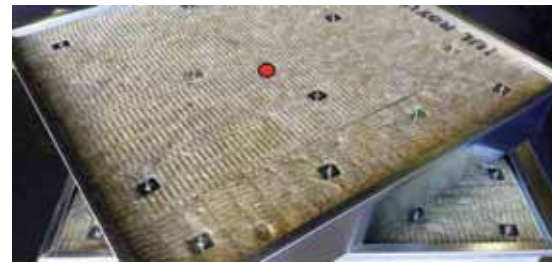


Figure 9. External temperature (To) sensor location

- The external back (To) sensor was installed on the external side of the insulation by drilling a small hole in the back pan. The back pan holes were sealed using the sealant used onsite and the hole was covered with a self-adhered membrane.
- The sensor is flush with the insulation and did not come in contact with the spandrel panel. A stopper was fastened to the sensor so that it cannot in anyway be extended too far and touch the panel.
- Wiring and thermistors were engineered to handle temperatures up to +100°C.
- This configuration will give the R value across the back pan but not the window. This is compliant with NBC A-9.36.2.4.(2) D – Note 5 that states “materials installed towards the exterior of a vented air space cannot be included in the calculation of effective thermal resistance of the assembly. (NBC A-9.36.2.4.(2) D – Note 5, 2015).

The Heat Flux sensor is connected to a 1000 times instrumentation gain amplifier then connected to a 24-bit high precision data logger A3 4R4V unit. To is installed through the back pan as shown in Figure 9 and is located behind the self-adhered membrane. Tb is taped with foil tape to the back pan and Ti is extended 4cm off the back pan. All wires are routed to the A3 data logger.



Figure 10. Typical sensor installation

The A3 8R and A3 4R4V units are both mounted at the central wall related to the adjacent sensor installation locations. These units are secured using Velcro to the back pan for easy removal. No further penetrations were made in the back pan to mount equipment.



Figure 11. Typical data logger and sensor installation

4. Pressure Differential Sensor Installation

One differential pressure sensor was installed between the Pressure equalized cavity (P2) and the interior airspace P1. This was done by placing a pressure tap through the assembly in similar fashion to the temperature sensors. The differential pressure is reported as $\Delta P = P2 - P1$. A positive pressure will mean that air is passing into the building and a negative pressure will represent air moving from the inside to outside. An attempt will be made to further enhance the pressure data acquisition by providing a tap to the exterior of the spandrel panel, P3. This valuable information will assist to further understand the pressure differentials across the assembly, see Figure 12.

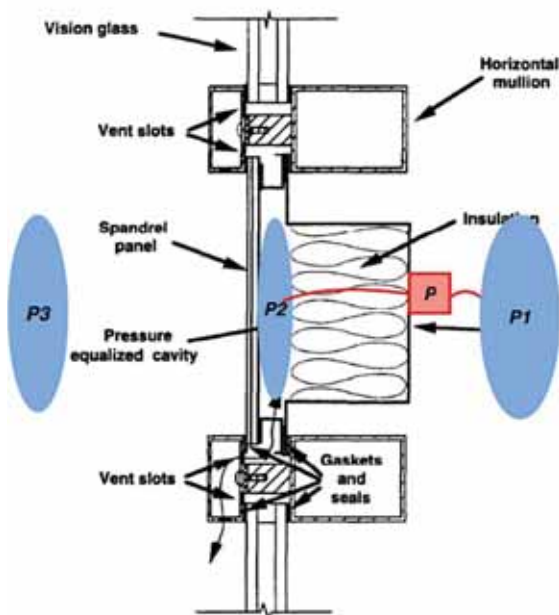


Figure 12. Differential Pressure Installation

A pressure hose connected to a differential pressure sensor is installed from the outer insulation behind the spandrel panel and the other hose of the sensor is located in the interior airspace.



Figure 13. Differential pressure sensor installation

5. Weather Station

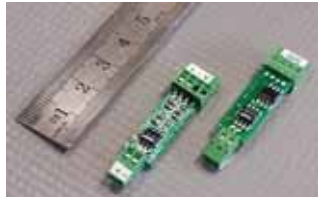
The weather station within the closest proximity is located at the University of Winnipeg as shown in Figure 14. This weather station has been attached to the Analytics profile so that weather data can be graphed alongside the other sensor data. In order to get more accurate results a weather station added to the roof of the building will be investigated as well as external temperature sensors on the 4 different wall facings of the building.



Figure 14. Weather station location

6. Data Acquisition Hardware

Sensors are routed to the data acquisition hardware that performs the analog to digital conversion. The sensors transmit their digital data wirelessly to a gateway located in a network room on the same floor. This gateway periodically synchronizes data with a cloud based network server where the data is archived for further analysis. Conversions and compound/virtual sensor sets are calculated on the network server and are available for graphing and further analysis using tools provided by the Analytics engine.



Sensors – Temperature, Heat Flux and Pressure



Data Acquisition and Analog to Digital Conversion



Gateway Synchronizes data with the Network Server



Analytics allows post processing, sensor comparisons and facilitates calculating new sensors based on multiple sensor inputs

7. Sensors

Heat Flux (HF)

The FluxTeq PHFS-09e heat flux sensor was designed to cover large compound areas so the heat flow of the insulation material and surrounding materials can be recorded. The Heat Flux sensors are connected to a instrumentation gain amplifier with 1000 times gain and then connected to a high resolution data acquisition unit

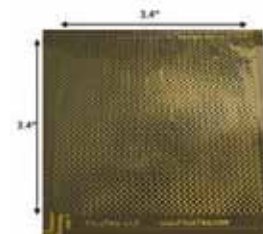


Figure 15. Heat Flux Sensor (without covering)

Temperature (T)

Epoxy Thermistor beads are used for temperature sensing.



Figure 16. Thermistor

Differential Pressure Sensors (DP)

Differential pressure sensors are integrated with the A3 Data Logger with an auto zero feature where the sensor will zero itself every 24 hours in order to negate any long-term drift of the pressure data being collected.

The sensor used is a 0.25" H₂O sensor or ± 62 Pa sensor made by AllSensors.



Figure 17. Differential Pressure Sensor

8. Results: 360 Main Street

The sensor installation at the RRC Skilled Trade and Technology Centre is complete however consistent data is presently unavailable, thus results for 360 Main Street will be presented and discussed at this time.

Data collection started on September 2017 and continues. Temperature data for this period is shown in Figure 18 on the East side and Figure 19 on the West side. Temperatures as high as 100°C were observed in the cavity between the back pan and glass. The boxed areas shown in Figure 18 are the areas explained further in Figure 20 to Figure 23.

Temperature

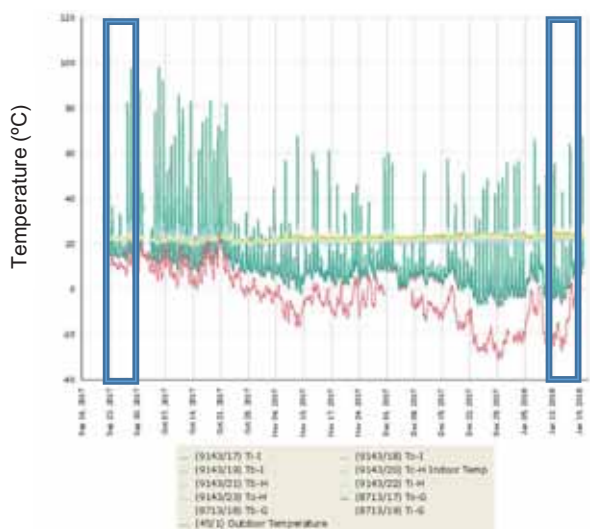


Figure 18. Temperature East

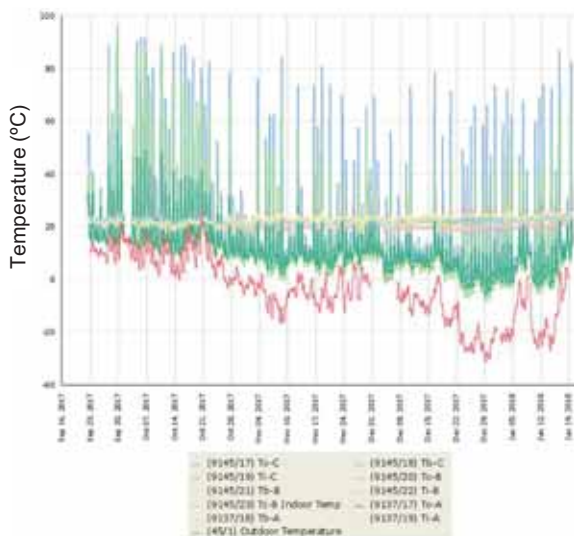


Figure 19. Temperature West

Dynamic Thermal Resistance

Outdoor and indoor temperatures as well as the heat flux and dynamic thermal resistance located on the East side are shown in Figure 20. A relatively warm week in September is shown.

During the transition of heat flow from negative to positive, the DTR experiences an off the scale reading due to a zero crossing instance, these are the out of range readings seen in the graphs.

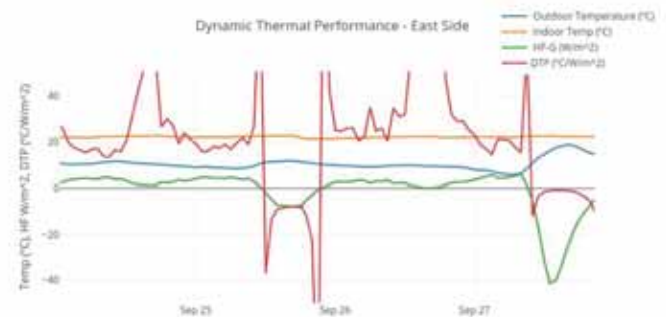


Figure 20. Dynamic Thermal Resistance – East September 2017 – warm week

At night, when the solar loading is minimized, an average DTR of ~ 15 $^{\circ}\text{C}/\text{W}/\text{m}^2$ is recorded indicating a thermal transfer from the warmer interior of the building to the cooler exterior of the building. During the day a DTR of ~ 10 $^{\circ}\text{C}/\text{W}/\text{m}^2$ is briefly recorded indicating a thermal transfer from the warmer exterior to cooler interior.

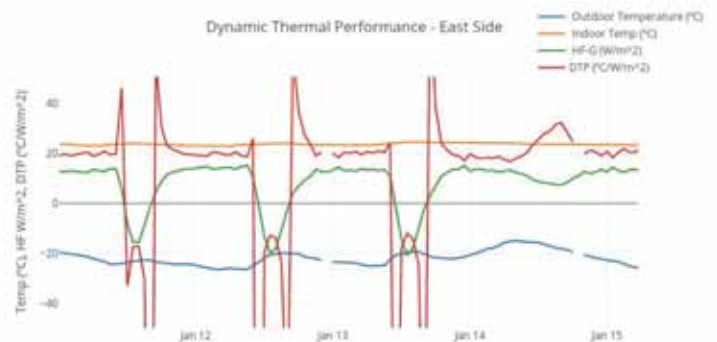


Figure 21. Dynamic Thermal Resistance – East January 2018 – cold week

Outdoor and indoor temperatures as well as the heat flux and dynamic thermal resistance located on the East are shown in Figure 21. A typical cold week during January is shown. During the winter months we see a DTR of 20 $^{\circ}\text{C}/\text{W}/\text{m}^2$. The solar loading during the day continues to cause a thermal transfer from outside to inside of ~ 10 $^{\circ}\text{C}/\text{W}/\text{m}^2$.

A similar trend was observed on the West side of the building as shown in Figure 22 and Figure 23.

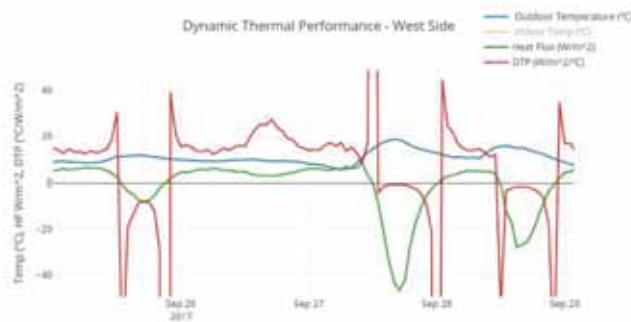


Figure 22. Dynamic Thermal Resistance – West September 2017 – warm week

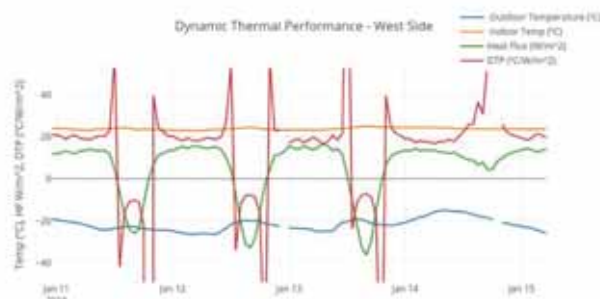


Figure 23. Dynamic Thermal Resistance – West January 2018 – cold week

Differential Pressure

The differential pressure sensor location at location H is situated from the building interior to the cavity between the back pan insulation and external façade. The differential pressure oscillated between -5 Pa and 85 Pa. The pressure sensor has a range of ± 62 Pa. The range between 62 Pa and 85 Pa is considered to be maxed values.

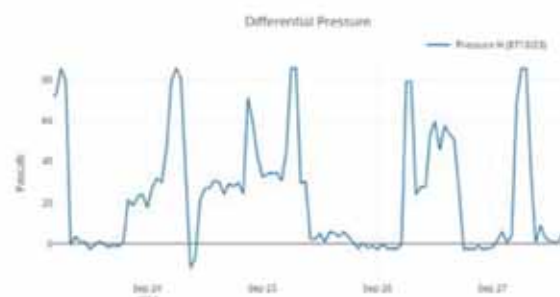


Figure 24. Differential Pressure - September 2017

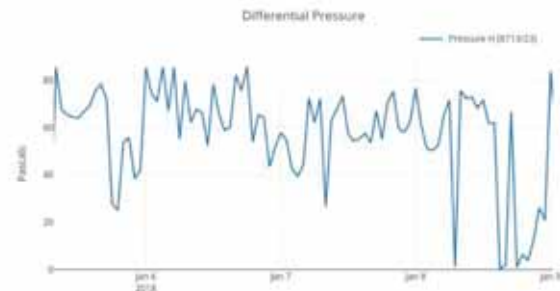


Figure 25. Differential Pressure January 2018

9. Conclusions and Outlook

The sensor network installed in the Red River College STTC building will be producing consistent data in early 2018. As a result an analysis cannot be compiled during the publish date of this paper.

An analysis of the back pan insulation installed at 360 Main Street, shows a Dynamic Thermal Resistance value during a stable range in the $8 \text{ }^{\circ}\text{C}/\text{W}/\text{m}^2$ range. The spikes in the DTR value are a result of the large temperature swings that occur due to solar radiation. Temperatures in the order of 100°C were observed in the summer, and temperatures in the 50°C range were observed in the winter, when outdoor temperatures were in the -25°C range.

The instrumented floor is used for staging the swing stages used to repair the other floors of the building. As a result, the interior temperature and pressure stabilization may not reflect the normal operation conditions of the building. Monitoring of the building will continue during normal occupancy of the building.

The preliminary findings obtained in this paper suggest significant variations between the computer modelled effective thermal resistance assumed in the design versus the actual Dynamic Thermal Resistance for the building envelope. Further research is required to develop a relationship based on additional data which will more accurately predicts the Dynamic Thermal Resistance for the building envelope at the design stage.

Acknowledgements

We gratefully acknowledge Red River College for the financial support to purchase and install sensors and electronics in these buildings.

We gratefully acknowledge Marwest Construction and ARTIS REIT for permission to install sensors as well as the financial support to instrument 360 Main Street.

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Wood Innovation Research Lab: An all-wood industrial building built to passive house standards

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Abstract:

The following case study on the Wood Innovation Research Lab, recently completed in Prince George, BC in March 2018 illustrates how designing to Passive House standards significantly reduced the operational energy of the building. The lab building pushes the envelope on what was previously thought possible in regards to energy efficiency of industrial buildings due to their large volume to surface ratio, relatively small floor area and high air change rate, and will be the first Passive House certified industrial building in North America.

Keywords:

Passive House, Wood construction, Industrial buildings

1. Introduction

Buildings and their construction contribute to the degradation of the environment through resource depletion and emissions. Approximately 40% of all CO₂ emissions are related to this sector and research suggests that the operation of a building accounts for 60-80% of the total energy use, making this phase the most significant contributor to the environmental impact of a building [1].



Fig 1: Wood Innovation Research Lab (courtesy of Stantec Architecture Ltd.)

Designing a building to a performance standard that has more stringent energy efficiency requirements for the building envelope than local building codes effectively reduces the operational energy of the building [2]. The Passive House Institute (PHI) developed one such standard, which takes a performance-based approach to building certification [3].

The University of Northern British Columbia, located in Prince George, BC, is committed to being a part of the solution and desires to see sustainable construction

grow in British Columbia. This commitment has resulted in the Masters of Engineering in Integrated Wood Design, a program that equips current and future design and construction professionals with the knowledge and tools necessary to increase wood design in industry and apply building science and sustainable design principles to future projects. The program is hosted in the Wood Innovation Design Center (WIDC), an 8 story glulam post and beam mixed use building with a cross-laminated timber core that was at the cutting edge of industry when it was first constructed.

As the program expands it has become necessary to increase the capabilities within the laboratory which are currently being limited by space [4]. As a result, UNBC's Wood Innovation Research Lab (WIRL) was recently completed in March 2018. The building was executed as a design-build and Passive House (PH) certification was written in as a requirement for the design which is particularly challenging for Prince George, BC which has a cold climate rating according to the PHI with 234 heating/cooling days per year. This harsh climate is one of the biggest challenges for achieving PH certification for the WIRL. The project team included Stantec Ltd who performed the architectural design and engineering, IDL Projects Inc. who conducted the construction and Herz & Lang who acted as the 3rd party PH certifiers.

The 10m tall lab building has a footprint of 30m x 30m on a raft slab foundation. The shop space is equipped with a concrete strong wall and floor and a crane bay, as well as a portion of the building that includes a two-storey office and classroom space. The structural system consists of a glulam post and beam superstructure with highly insulated wall and roof panels.

2. Passive House certification

Passive House design focuses on five main principles to achieve a high performing building [3]; 1) Increased thermal insulation in the building envelope to minimize heat losses, for most cool and temperate climates this will require a maximum heat transfer coefficient (U-value) of $0.15 \text{ W/m}^2\text{K}$. 2) High performing components such as windows and doors with increased insulation in the frames and low e-glazing with argon or krypton coatings and multiple panes with thermal spacers. A passive house window should have a maximum U-value of $0.8 \text{ W/m}^2\text{K}$. 3) Heat recovery ventilation (HRV) is required with a minimum efficiency of 75% according to the PHI method of calculation where no recirculation is allowed. A HRV unit transfers heat from exhaust air to the fresh air intake, reducing the need to heat up incoming outside air with the added benefit of improving air quality through filtration. 4) Increasing air tightness in order to minimize heat loss through uncontrolled air leakage through the building envelope. And 5) avoiding thermal bridges in the design of edges, corners, penetrations and connection details. The following criteria must be met in order to achieve passive house certification [5]:

- Space heating/ cooling: $<15 \text{ kWh/m}^2$
- Primary energy demand $< (120) \text{ kWh/m}^2\text{a}$
- Air tightness: $<0.6 \text{ ach @50 Pa}$
- Thermal comfort: $<10\%$ time at a temperature $>25^\circ\text{C}$

Designers use the Passive House Planning Package (PHPP) [5] to model the building and verify whether the final project has met all the requirements for certification.

3. Challenges specific to the WIRL

When completed and certified, the WIRL will be one of the first buildings of its kind in the International Passive House database, which includes over 4000 projects worldwide [6]. The WIRL will be the first certified PH industrial building in North America [6]. The challenges associated with achieving a high performing industrial building can be partially attributed to the nature of the building utilization as explained in the following sections.

The requirement of large bays results in high volume (9686 m^3) to treated floor area (1042 m^2) ratio. The large volume of space to heat and small treated floor area is challenging since the maximum heating demand is established on a m^2 basis.

Reducing thermal losses through the concrete foundation is also challenging due to the fact that a portion of the foundation is a “strong floor”—a high capacity 1m thick section of reinforced concrete that will be used for structural testing. A high strength and density EPS insulation had to be special ordered for

installation below this portion of the building that would be experiencing higher than normal forces.

The facility has several large pieces of highly specialized equipment installed for research and teaching purposes. The use of this equipment presented a unique challenge for modeling the primary energy demand of the building, which is restricted to $(120) \text{ kWh/m}^2\text{a}$ [3]. There are no well-established values for utilization of such equipment in the PH design framework. It is important to have a level of accuracy for these values since the use of the equipment results in internal heat gains, which ultimately affects the sizing of the furnace for the building. These values were entered into the model based on the client’s predictions of utilization. An example of this specialized equipment is the large hydraulic power unit that will be used to create the forces applied to the test structures. When in operation this unit can produce approximately 90 kWh of heat at peak consumption. To compensate for the heat produced, a cooling unit was also required for the WIRL.

There were certain unavoidable heat losses such as the large volume of air vented when the dust extraction unit is in operation. The bay doors used to bring truck loads of material in and out of the lab had the potential to act as large thermal bridges when closed due to the lack of high performing products currently available on the market, when the doors are opened there are significant holes in the envelope for heat loss. High performing bay doors were ordered from a European manufacturer to minimize the thermal bridging. These weak points in the thermal envelope and air tightness were compensated for with the additional insulation in the walls, foundation and roof. The walls are over 500 mm thick, framed with upright wooden trusses in 10 m tall panels. The sloped Expanded Polystyrene (EPS) insulation on the roof has an average thickness of 560 mm and the concrete slab is insulated with over 200 mm of EPS.

4. Long Term Monitoring

Due to the innovative nature of the project, there are very few buildings that can be used as a comparison for the WIRL [7]. It was therefore identified early on in the project that it would be useful to have long term monitoring of the thermal performance of the building as well as metering to confirm any assumptions made in the models for energy demand. Temperature sensors were installed in grids along the Southwest corner of the foundation and wall sensors were installed in 1 panel on each of the North and South faces of the building as seen in the Figure 2

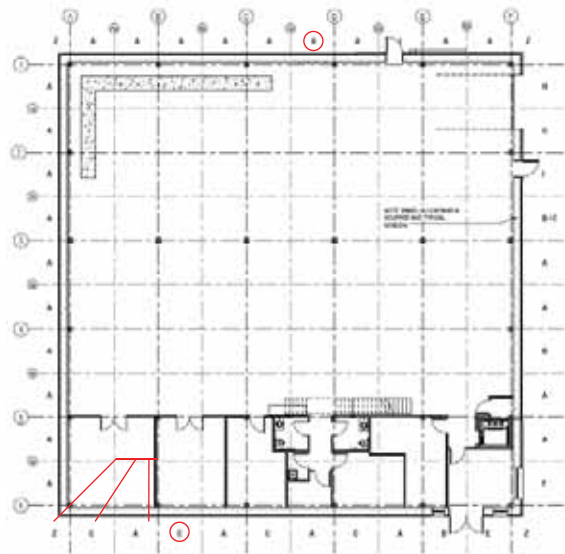


Fig 2: North and South Wall panel locations and location of sensors in the Southwest corner of the foundation (Floor Plan Courtesy of Stantec Architecture Ltd.)

There are 6 strings of temperature sensors in the foundation, 3 strings located between the gravel and the insulation and 3 strings located between the insulation and the concrete, as detailed in Figure 3.

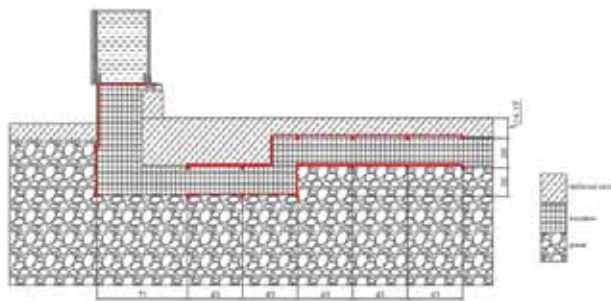


Fig 3: Section view of floor sensors (Lichtenstrasser 2017)

The interior condition of the building as well as exterior weather conditions will be monitored and recorded in order to establish the boundary conditions for the heat and moisture transport through the wall assemblies. The temperature and relative humidity sensors are located at various intervals within the cross section of the panel; along the wood-framing member as well as within the insulation cavity. The cross section of sensors is repeated at the top, middle, and bottom of the panel to establish heat and moisture transport through the wall in two dimensions. The location of the sensors within each panel can be seen in Figure 4. The wall sensors were installed on site before the blown in insulation was applied to the walls.

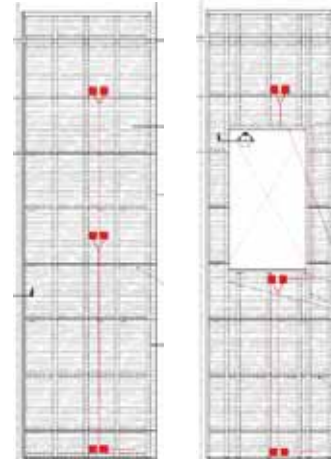


Fig 4: Location of temperature and relative humidity sensors within the wall panels

Long term monitoring of the wall panels will offer insight into the durability of the building design as well as offer a comparison between modeled behavior of the building and reality. The long-term data from the temperature and humidity sensors as well as from the meters for electrical usage will be used to verify the overall performance as predicted by PHPP.

5. Results and discussion

The key PH parameters that were achieved are summarized in Table 1 and the thermal performance of components is summarized in Table 2.

Table 1: Verification Summary¹

Parameter	Value	Units
Treated Floor area	1042	m ²
Volume of ventilated space	9686	m ³
Heating Demand	14	kWh/m ² a
Heating load	15	W/ m ²
Primary Energy Demand	120	kWh/m ² a
Primary Energy Renewable Demand	65	kWh/m ² a
Airtightness (assumed value until blower door tests can be conducted)	0.6	ach @50 Pa

Table 2: Summary of Components¹

Component	U-Value (W/m ² K)
Walls	0.079
Roof	0.056
Floor	0.166
Windows (38.6 m ²)	0.67
Doors (11 m ²)	0.91-0.97

¹The values taken from the PHPP file as well as design details that were key for the WIRL certification have been provided by Stantec Ltd.

6. Conclusions and outlook

The WIRL provides an opportunity to showcase wood construction, to pioneer the application of wood in industrial buildings as well as to go beyond the successes of other significant wood construction projects in North America by designing to PH standards. The WIRL targets a building category that has few examples of wood design or high efficiency construction and is generally lacking in research.

Acknowledgements

This research was partially funded by the Pacific Institute for Climate Solutions as well as Forestry Innovation Investment Ltd. The authors would like to thank Stantec Ltd, IDL Projects, and UNBC's Facilities team for providing information throughout the design and construction process that was used in the writing of this case study. Special thanks to Conan Veitch, UNBC for assisting in the building sensor design and to Johannes Kaufmann, Thomas Lichtenstrasser and Markus Haberknapp for assisting in the assembly and installation of the sensors.

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Life cycle assessment supports wood construction and Passive House design in industrial buildings

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Abstract:

There are many strategies being developed to create greener buildings that have a smaller impact on the environment, but how do we measure this impact and compare approaches? Life cycle assessment is a scientific methodology that has been developed in order to systematically analyze the environmental load of processes and products over their life. A life cycle assessment conducted on UNBC's Wood Innovation Research Lab establishes sound environmental justification for designing to PH standards and building with engineered wood products as a primary structural material.

Keywords:

Life cycle assessment, wood construction, passive house

1. Introduction

Buildings and the construction sector greatly contribute to the degradation of the environment during each stage of their life including; material extraction, transportation, manufacturing, construction, operation, and end of life building stages. These impacts occur due to resource consumption and the production emissions and pollutants [1]. The following case study illustrates that careful material selections for the structure and envelope of a building significantly decreases the environmental footprint of an industrial building.

Life cycle assessment (LCA) is a scientific methodology that has been developed in order to systematically analyze the environmental load of processes and products over their life [2]. A comparative LCA was conducted on the Wood Innovation Research Lab (WIRL), a lab building located in Prince George, BC and designed using wood and to Passive House standards, completed in March 2018.



Fig 1: Wood Innovation Research Lab (courtesy Stantec Architecture Ltd.)

The LCA identified materials and components within the building that have the most environmental impact. It also highlighted the magnitude of the impact of materials vs. operational energy by comparing steel and wood buildings designed to different performance

standards. The study aimed to reveal whether the increased material associated with passive design and the selection of timber rather than steel will have the desired environmental impact reduction on an industrial building that is commonly seen in residential and commercial buildings.

2. Methodology

Four design variations were made to the UNBC Wood Innovation Research Lab base model and analyzed for operational energy and embodied impacts over the lifetime of the building. The models were compared in order to determine which design has the lowest environmental impact. The four model variations are as follows: 1) wood construction designed to code 2) wood construction designed to Passive House (PH) standards 3) steel construction designed to code 4) steel construction designed to PH standards. The comparison serves to isolate the impact of material selection and design from other key factors such as variations in climatic conditions, design codes, material and energy sources, geometry and location, all of which commonly vary between comparisons by keeping all other aspects of the LCA and energy models consistent.

The operational energy is calculated using the Passive House Planning Package (PHPP) provided by the Passive House Institute [3]. The energy consumption calculated was then factored into the Athena LCA models by multiplying the heating energy demand by the treated floor area for each model. The embodied energy of the materials as well as the overall environmental impact of each design is calculated using the Athena Impact Estimator for Buildings v.5, which uses the TRACI database for the life cycle inventory values [4]. The LCA was conducted according to ISO 14040 [2].

Passive House design focuses on five main principles to achieve a high performing building [5]; 1) Increased thermal insulation in the building envelope to minimize heat losses, for most cool and temperate climates this will require a maximum heat transfer coefficient (U-value) of 0.15 W/m²K. 2) High performing components such as windows and doors with increased insulation in the frames and low e-glazing with argon or krypton coatings and multiple panes with thermal spacers. A passive house window should have a maximum U-value of 0.8 W/m²K. 3) Heat recovery ventilation (HRV) is required with a minimum efficiency of 75%. A HRV unit transfers heat from exhaust air to the fresh air intake, reducing the need to heat up incoming outside air with the added benefit of improving air quality through filtration. 4) Increasing air tightness in order to minimize heat loss through uncontrolled air leakage through the building envelope. And 5) avoiding thermal bridges in the design of edges, corners, penetrations and connection details. The following criteria must be met in order to achieve passive house certification [5]:

- Space heating/ cooling: <15 kWh/m²
- Primary energy demand < (120) kWh/m²a
- Air tightness: <0.6 ach @50 Pa
- Thermal comfort: <10% time at a temperature >25°C

A few key challenges for obtaining Passive House certification of the WIRL include; Prince George's cold, northern climate, the high volume to surface area ratio, thermal bridging associated with the concrete foundation and strong-wall as well as the bay doors which are large thermal bridges when closed due to the lack of high performing products currently available on the market, when the doors are opened there are significant holes in the envelope for heat loss.

The scope of the LCA can broadly be described as cradle to grave. The object of assessment, which is consistent for all the models includes: The building envelope including windows and doors, the superstructure, foundation, and interior partition walls and floors. The scope does not include the concrete and rebar within the strong wall and strong floor which is technically a part of the structure of the building but was classified as a major piece of testing equipment. The strong wall and floor accounted for over 30% of the environmental impacts if included in the "Wood to PH model". The operating energy, which includes the natural gas for heating and the electricity is also included and varies between the "Designed to Code" and Designed to Passive House Standard" models. It is important to note that the life cycle stages "Installed Product in Use, Repair, Refurbishment, Operational Water Use, Waste Processing and Beyond Building Life" were considered to be outside the scope of the assessment [6].

The functional unit for this project is one industrial building with a 30x 30m footprint located in Prince

George BC. The expected service life of the building is 60 years.

3. Model descriptions

The following sections outline the main differences between the steel and wood models as well as the modifications made between the built to code and built to passive house standard models.

3.1 Designed to code

The key differences between the models designed to code and designed to PH standards is the thermal performance of the walls, roof, foundation, windows, doors and the selection of ventilation system. The WIRL is a non-residential occupancy building with a floor area greater than 300 m² therefore the designed to "code models have been designed to comply with the National Energy Code of Canada for Buildings (NECB) 2015 [7].

The resulting design for the Code model outer walls is 39 x 184 mm studs filled with mineral fiber batt insulation. The raft slab foundation is fully insulated with 200 mm of EPS. The windows have double paned glass and average thermal performance. The bay doors are not insulated and the street entrance doors are either solid wood or hollow aluminum for the wood and steel models respectively. The ventilation system for all four of the models has been modeled with a ventilation requirement of 30 m³/P*h and an average room height of 6.7m. The Code models have no heat recovery and the dust extraction system will result in significant energy losses as the purge volume was modeled at 10,000 m³/h. The airtightness of the buildings meets the NECB requirements of 0.2 L/(s*m²) at a pressure differential of 75Pa [7]. The Code models have a heating demand of 167 kWh/m²a and an electrical demand of 38228 kWh/a.

3.2 Designed to PH standard

The models designed to PH standards have modified wall, roof and foundation assemblies that allow for a greater airtightness, thicker insulation and reduced thermal bridges. Both the Wood to PH and Steel to PH models have exterior walls constructed with 500 mm deep upright wooden trusses filled with blown in mineral wool insulation. It was unrealistic to construct an airtight, thermal bridge free envelope with steel framing members which resulted in the Steel to PH model having wood framed walls. The concrete slab used for the foundation is completely insulated using 215 mm of high density EPS. The windows used in the PH models have triple paned glass, a thermal spacer between panes and high levels of insulation within the frame. The bay doors have been improved in the PH models by using a highly insulated overhead door based on recommendations from the 3rd party certifiers. Even with the highly insulated solution the bay doors represent a significant challenge and a weak

spot in the thermal performance of the building. The ventilation system however is the most important component in achieving PH standards. The system selected for the PH models has a heat recovery efficiency of 81%. An airtightness of 0.6 ach @50 Pa, the minimum requirement for PH certification, is assumed for the PH models. The heating demand for the PH models is 15 kWh/m²a and the electrical demand is 38228 kWh/a.

Table 1: Envelope thermal performance (U-Value W/m²K) of each model

Assembly	Wood to Code	Wood to PH	Steel to Code	Steel to PH
Roof	0.180	0.056	0.180	0.056
Walls	0.234	0.079	0.247	0.079
Foundation	0.182	0.166	0.182	0.166

3.3 Wood structure

The wood models are comprised of a glulam column and beam structure with dimensional lumber wooden roof trusses. Glulam columns separate the lab space into two main bays. The outer wall assemblies will be light wood frame construction to the exterior of the vertical load bearing columns. The interior walls are 38x 89mm wood construction with gypsum wall board finishing's. The level 2 office floors are comprised of glulam beams, wood I-joist and plywood sheathing.

3.4 Steel Structure

The steel models are comprised of a wide flange steel post and beam structure with a non-structural envelope. The sizing and spacing of the components was estimated according to the Athena auto generated sizes based on the parameters and loading conditions entered [6]. The level 2 floor and roof are comprised of open web steel joists with concrete topping. The interior partition walls are made of light gauge steel C joists, 39 x 152 mm spaced 400 mm o.c. with a span of 5.5 m, which is the maximum allowable span in the Athena model [6].

4. Results and discussions

Athena gives midpoint indicators in 8 different categories [8]. Global Warming Potential (GWP) will be used as the impact indicator in the following discussion.

The increase in impacts from the material associated with designing to Passive House standards rather than to local building codes is 12% for the wood models, as seen Figure 2 when you only consider the product phase of the LCA.

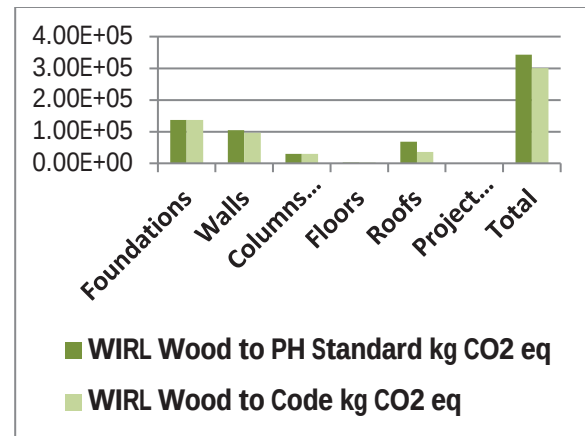


Fig 2: Increase in GWP of the materials when upgrading from code to PH

When operational energy is also factored into the comparison it can be seen in Figure 3 that despite the increase in impacts for the product stage, there is an overall reduction of 70% of the GWP due to the dramatic reduction in heating demand for a PH building compared to code.

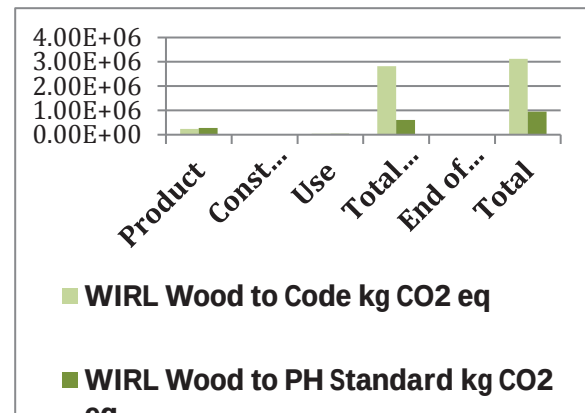


Fig 3: Decrease in GWP of the whole building LCA when operational energy is considered

Similarly, Figure 4 shows the material selection for the structural system had a relatively small impact of a 22% increase on the product phase of the LCA results if constructed with steel rather than wood.

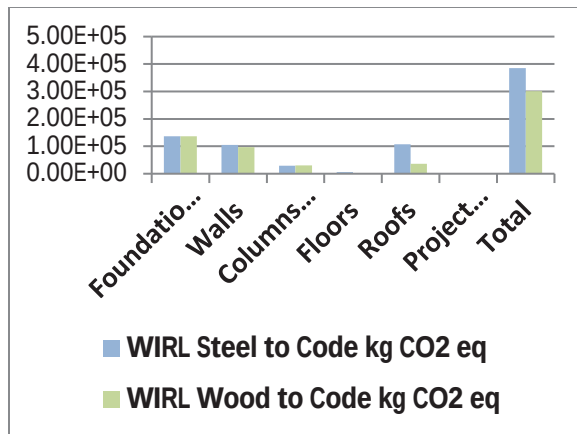


Fig 4: Increase in GWP of the materials when designing with steel rather than wood

When all four models are compared side by side for total GWP from the material product phase and the operational energy it can be seen in Figure 5 that whether designed with steel or wood, the code models had over 3x the GWP of the PH models.

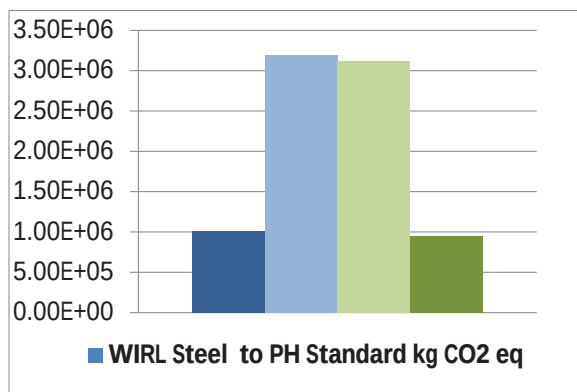


Fig 5: Whole building GWP comparison of all models

According to the above results it is more critical to design a building to a high performance design standard than to lower the impact of the materials, but as Table 2 illustrates, as a building approaches high performance, the material selection becomes a larger piece of the overall impact and therefore has increasing importance as the design improves.

Table 2: Increasing impact of material selection as operational performance improves

Project Name	Product, Construction and Use (kgCO ₂ e)	Total (kgCO ₂ e)	Material Selection Impact (% of total GWP)
Wood to Code	2.92E+05	3.12E+06	9%
Wood to PH	3.33E+05	9.50E+05	35%

5. Conclusions and outlook

The LCA results illustrate that achieving high thermal performance by designing to a higher than code standard has greater significance than the material selection when it comes to reducing the environmental impact of a building. For high efficiency buildings where the operational energy is relatively low; the embodied energy of the material selection becomes a significant design decision as it greatly impacts the overall environmental footprint of the building. The WIRL LCA comparison establishes sound environmental justification for designing to PH standards and building with engineered wood products as a primary structural material. The WIRL is an innovative building that pioneers the application of wood and high performance standards in industrial buildings.

Acknowledgements

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Recycled aggregate concrete & its application in sustainable development

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Abstract:

Now-a-days, sustainability in construction is an important concern for the betterment of world environment. Construction activities especially concrete construction involves a large amount of greenhouse gas emissions and extraction of materials from natural resources. Also, Construction & Demolition waste generated by this industry is at the top of non-biodegradable waste of the municipal solid waste (by weight). It is the need of the hour to establish a process of recycling and utilizing it in construction industry in addition to its traditional use as landfills. Recycled Concrete Aggregate produced by crushing and processing old concrete, and using these aggregate in production of new concrete, can be a sustainable solution. This paper presents review of research published on the Recycled aggregate concrete and discusses case study of a live project of sidewalk construction located in the Okanagan valley, (Kelowna).

Keywords:

Recycled Concrete Aggregate, Recycled Concrete, Sidewalk, Compressive Strength.

1. Introduction

Construction industry is the largest contributor to global carbon foot print, utilizing around one third of the world resources that include usage of 12% water and 40% of all extracted raw materials [2]. In addition, this industry contributes to 40% of the world's waste in form of Construction & Demolition (C&D) waste[1]. C&D waste is a substantial component of the municipal solid waste and can range from 20%-50% or even more. It is mainly composed of wood products, asphalt, drywall, concrete and masonry. C&D waste has affected the ecosystem adversely with the increase in environmental pollution (water, soil & air), causing climatic changes and unbalancing flora and fauna. Additionally, it is also a source of health hazards (production & spread of pests) and use up of valuable public space (landfills). C&D waste has high residual value as 75% of this waste can follow the three R's of recycling (reduce, reuse, and recycle)[2].

Sustainability in the construction industry started gaining attention after World War II. In fact, many developed countries have taken initiative on emphasizing the use of waste/recycled material in construction by providing incentives, penalizing the use of naturally extracted materials and by raising prices of landfill sites. Additionally, countries like Denmark, Netherlands and Japan are very successful in attaining sustainable construction[2]. Above all, China is participating with progressive rate and was successful in publishing a regional code for the use of recycled concrete in 2007 i.e. "Technical code for application of recycled concrete"[3].

However, the recycling rate of C&D waste in Canada is very low compared to other developed countries despite continuous emphasis by Federal Government

on opting green techniques for construction and infrastructure management. C&D waste produced by this industry per annum is approximately 33% of the municipal waste out of which 27 % is fed to landfills. Canada, no doubt has vast land, but the fast urbanization of cities will soon lead to burden landfills. According to CIC 2009 report, by year 2027 nearly 80% of the public infrastructure will attain its design life and will require to be replaced. Under these circumstance, it will be a major concern for mega cities where landfills within cities are nearly full and establishment of new landfills will add budget, long distances to transport and more burning of fuel. As matter of fact, non-biodegradability, non-compressibility and massive amounts are the problems associated with C&D waste which subsequently reduce the potential capacity of landfills[2].

Moreover, concrete is also a major source of C&D waste in Canada's construction industry contributing around 52% by weight to it [4]. If concrete from C&D waste is reused as Recycled Concrete Aggregate (RCA) it will not only reduce the permanent load from landfills but will also protect the environment. In fact, there is huge potential of using RCA in concrete as 70-80% volume of concrete is build by coarse aggregate[2].

The purpose of this study is to provide a short review of current research about recycled aggregate concrete. The study will focus on the properties of RCA and concrete composed of it and compares them with those of conventional concrete. In the end, a case study is provided that demonstrates the log of compressive strength development with time, having results from non-destructive testing of a sidewalk constructed by RCA in Kelowna, Canada.

2. Recycled Concrete Aggregate

Recycled concrete aggregate (RCA) and virgin aggregate behaves differently because of the attached mortar to RCA, whose quantity may vary from 20%-30% volumetrically depending upon the processing method and the type of parent concrete [3]. Also, the percentage of attached mortar varies with the size of aggregates and will decrease as the size of aggregate increases. In addition to this, with change in size of aggregate from 4mm to 32mm the percentage of attached mortar decreased from 60% to 35%. According to study by XIAO et al [3], the properties of RCA that effects its performance are lower bulk & saturated-surface-dry density, higher water absorption, porosity, crushing index and clay content. The reason being that attached mortar is lighter in weight which results in decreased density and is highly porous, which makes it a good medium to hold water. At the same time, it is found in literature that relation between the absorption percentage and grade of parent concrete are independent and only increase providing that increase in the size of aggregate [6].

Besides, high water absorption and low density are negative attributes of RCA which limits its acceptance criteria on these two material properties in different standards [5]. However, the maximum limit on water absorption of RCA vary from standard to standard for different countries. The Australian standard (AS 1996) limit absorption percentage to ≤ 6 . The Japanese international standard (JIS 2011, 2012a,b) put the bar very low to $\leq 3\%$ for aggregates produced from parent concrete of nominal strength 45 MPa or less. Same limitation of 3% is applied by Korean standard 2002 (KS F 2573). German standard (DIN 2002 (4226-100)) restricted this value to $\leq 10\%$ for RCA produced from concrete chipping and crusher sand. Although, Specifications developed by the RILEM (1994) committee stands with the German Code DIN (2002). Further, the acceptable range for saturated surface dry density ranges from 2000 to 2500 kg/m³ [6]. On the other hand, Chinese Technical code for application of recycled concrete (DG/TJ08-2018-2007) limited the water absorption to $\leq 7\%$ and 10 % for structural & non-structural concretes respectively[3].

Moreover, the shape of RCA is smoother with less edges because of attached mortar thus, increasing the workability of Recycled Concrete at same water cement ratio. Also, the results of Aggregate crushing value under sustained loading and Los Angeles abrasion tests, to check for durability characteristics of RCA, had been found to be poorer compared to those of natural aggregates. This helps to conclude that interfacial transition zone between attached mortar and virgin aggregate is the weakest link for RCA [5].

3. Recycled Concrete

Recycled concrete (RC) composed of RCA behaves contrarily to conventional concrete (CC) mainly because of inherent properties of RCA. Typical factors affecting the properties of RC are similar to CC with addition to percentage replacement of RCA.

Not to mention this, concrete is always designed on its target 28 days cylindrical compressive strength. Durability and long-term behavior of concrete can be precisely predicted based on this mechanical property[6]. Many researchers have reported that it is possible for RC to achieve similar 28 days compressive strength to CC with 30% replacement of NCA by RCA and at the same water/cement (w/c) ratio. In addition to this, for replacement ratios more than 50% to 100%, w/c ratio required to lower by 4-10% to maintain the same target strength, otherwise the compressive strength is reduced by 20-25%[5]. More importantly, Kisku et al. [6] described that if w/c ratio of the mix is reduced by 10% by adding the cement in same percentage than it is possible to achieve comparable strength between RC and CC. Further, RC required 0.05-0.1 lower w/c ratio for compressive strength alike to CC [6]. Additionally, when it comes to the comparison between effects of saturated surface dry and air dry condition of RCA, the former will produce lower strength concrete. The reason being increase of water content discharging from the pores of attached mortar in hardened concrete [7].

Moreover, compressive strength of RC is very much dependent on the quality of RCA which is majorly based on strength of its source concrete. McNeil et al. [5] discussed the likelihood of developing RC stronger than CC if source of RCA is of high strength concrete. RCA obtained from high strength concrete has less water absorption, more density and low values of crushing & Los Angeles abrasion tests because of well hydrated compact mortar. On the other hand, Kou & Poon [8] studied the long term compressive strength of RC made with 20%, 50% and 100% RCA for a period of 5 years. They found that rate of gain of strength by RC is 15% more than CC average over the studied time.

4. Case Study

The case study discussed here is about Recycled Concrete (RC) sidewalk constructed on Cadder Ave, in Kelowna, British Columbia, Canada. This project is the result of research collaboration between ALAMS research group (UBCO), City of Kelowna and OK builders. This sidewalk has a length of 200m and was constructed in 2013 with RC having 0%, 30%, 50%, 70% and 100% replacement by RCA. The construction of side walk is shown in Fig 1.



Fig 1: Construction of sidewalk with RC

RC was mixed in concrete mixing trucks like conventional concrete (CC) and all the panels after pouring were marked with RCA content for tracking of their performance. Fig 2 shows panels with 50% RAC content (left) and 30% RCA content (right).



Fig 2: Marking of side walk made with RC

In addition to this, concrete cylinders were also casted during the pouring of sidewalk for laboratory testing. In the laboratory, compressive strength of RC for all replacement ratios, i.e. 0%, 30%, 50%, 70% and 100% was evaluated up to the age of 120 days and are plotted as graph shown in Fig 3. It is clear from the graph that rate of gain of strength for concrete made from 0% and 100% RCA is exactly same till 28 days. 50% RCA shows the lowest strength at 28 days while 30% and 70% lie in middle of strength trends. Further, remarkable increase in strength gain was shown by 30% RCA after 28 days which reached to CC (0% RCA) at the age of 120 days. Further, throughout the testing period, the rate of gain of strength for 50% RCA and 70% RCA replacements was mild and were nearly similar to each other.

Even more, visual observation about performance of RC sidewalk is satisfactory (Fig 4) and is confirmed from City of Kelowna maintenance office recently. The serviceability of RC sidewalks was highly appreciated with no complaints from the users.

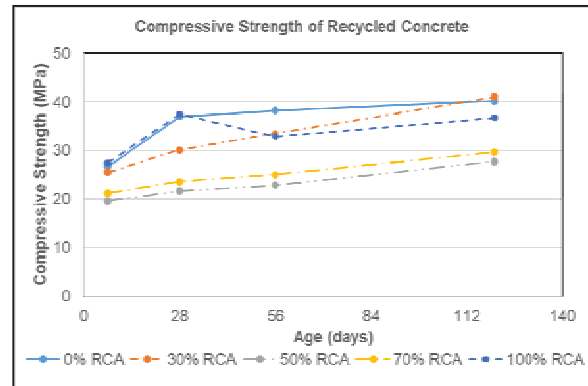


Fig 3: Compressive strength of concrete for different percentages of RCA for 120 Days.



Fig 4: NDT Compressive strength of RC

Long term compressive strength was evaluated by Schmidt Hammer, a Non-Destructive Test (NDT) (Fig 5).



Fig 5: NDT Compressive strength of RC

Additionally, the results of NDT performed after 2 years of construction are presented graphically in comparison with 28 Days compressive strength in figure 6.

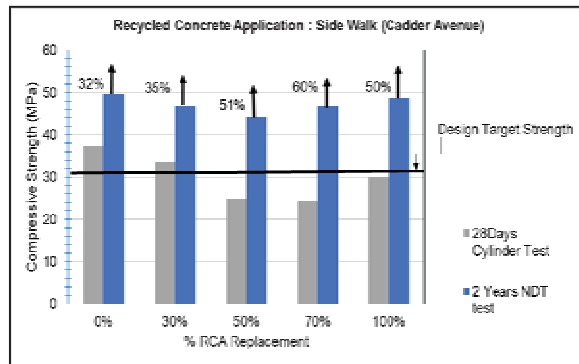


Fig 6: Comparison between 28 Days Compressive strength and NDT test results

From Fig 6, it is seen that the concrete made from RCA showed high improvement in strength over study time. Specifically, compressive strength for the 70% RCA replacement was enhanced the most (by 60%), followed by 50%, 100% and 30% RC. The reason of improved strength with age is stored water in adhered mortar, which acts as continuous source of water for hydration of cement over time and facilitate strength development.

The results of the case study are also supported by study of Kou & Poon [8]. In a period of 2 years, RC was subject to load by pedestrians and extreme weather change. It withstands all loading and exposure conditions, equivalent to natural aggregate concrete and can be recommended for use in sidewalks safely.

5. Conclusions

This study showed that the properties of recycled aggregate concrete as reported in literature (particularly compressive strength) are slightly inferior compared to conventional concrete considering its 28 days target strength. Proper techniques mentioned in literature can be adopted to enhance the properties of recycled aggregate concrete. The case study discussed here about the recycled concrete sidewalk showed that there is significant difference in time phased compressive strength of recycled concrete and conventional concrete, and is in agreement with the result of previous studies. This information can be helpful to advance with Recycled Concrete as sustainable material.

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Operational performance management of multi-unit residential buildings

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Abstract:

Post-occupancy performance evaluation (POPE) is an important process in the life cycle management of built infrastructure. Since Canadians spend approximately 80% of their time indoors, operational management of built environment is of extreme importance. Due to the increased popularity of multiunit residential buildings (MURB) in urban areas, there is a need to scrutinize the operational management MURB. Despite the large body of knowledge available on building rating systems and POPE, there are no comprehensive tools that assist operational management in a user-friendly manner. Moreover, popular building rating systems overlook the operational performance of the built environment. The objective of this paper is to develop a POPE tool for MURB. The level of service (LOS) based POPE tool will assess the operational performance in terms of safety, customer satisfaction, reliability, responsiveness, environmental acceptability, and occupant health, in the post-occupancy stage. Fuzzy synthetic evaluation (FSE) was used to synthesize the operational performance of MURB related to different performance categories. The LOS index and performance benchmarks are expected to assist in the decision making of strata management companies in maintaining and enhancing their service. Findings from the study help improving the quality of the service provided to building tenants. Furthermore, continuous monitoring will allow environment-conscious operation of MURB.

Keywords: Multi-Unit Residential Buildings, Level of Service, Fuzzy synthetic evaluation.

1. Introduction

United Nations has identified that densification is necessary for socioeconomic and environmental sustainability of urban areas [1]. According to statistics, urban population growth rate is higher than the total global population growth rate[2][3]. Consequently, there is a growing demand for housing in the urban context, which would be primarily provided by multi-unit residential buildings (MURB). Increased demand for built environment unfolds numerous challenges that primarily affect the environment. Buildings use about 40% of global energy, 25% of global water, 40% of global resources, and they account for 33% of greenhouse gas (GHG) emissions approximately [4]. Due to the high number of hours spent indoors, systems that control building indoor conditions have a direct impact on occupant health [5].

There is an increasing demand to enhance the triple bottom line (TBL) performance (i.e. environmental, social, and economic) of built environment including MURB. Post occupancy performance evaluation (POPE) is important to ensure that building achieve TBL targets.

Even though there are many building rating systems in the industry and literature, various drawbacks of building rating systems have been highlighted. A major criticism for building rating systems includes time spent for project evaluation and complexity [6][7]. No further evaluation of the building is carried out after the initial rating [6]. Furthermore, many building rating systems does not incorporate social,

environmental, and economic criteria simultaneously. Although many buildings do not perform as planned, performance assessment in the operational stage has been an unpopular initiative in the building industry. Accurate and current building performance monitoring enables more proactive building management [8]. A comprehensive literature review revealed that there are only a few comprehensive facilities rating systems for MURB.

Innovative POPE methods are required to monitor and manage TBL performance of MURB. Ruparathna et al. (2017) developed an uncertainty based operational rating system for buildings using level of service (LOS) concept [9]. LOS for buildings is defined as the assessment of the operational performance provided to the building users, society, and environment [9]. LOS of building has been evaluated based on criteria such as, safety, customer satisfaction, quality, quantity, capacity, reliability, responsiveness, environmental acceptability, cost, and availability [10][11][14].

Safety: MURB should ensure healthy indoor air quality, ergonomic design, electrical safety and accident prevention and measures to prevent potential natural and human-caused hazards to tenants [13].

User satisfaction : MURB should satisfy the expectations of the tenants [15].

Quality: MURB facilities management services should be of high quality, reaching the service standards [16][17].

Quantity: MURB should be able to serve the current demands from a building.

Capacity: MURB management should be able to serve expected service demand in future.

Reliability: Facilities management service of the MURB should be dependable and accurate [18].

Responsiveness: Tenants should be provided speedy service with regards to the facility [18].

Environmental Acceptability: MURB should ensure environmental performance of the building

Cost: Cost effective building operation should include attributes such as low building operation and maintenance costs and longer life span [19]

Availability: Facilities services should be delivered according to the agreed service function [20].

There are no LOS based POPE methods for MURB. Therefore, the objective of this paper is to develop an operational rating system for MURB. The building LOS assessment method developed by Ruparathna et al (2017) was customized to suit MURB. Use of fuzzy logic will enable incorporating vague, incomplete, and qualitative data into the operational rating. A web based tool was developed to support wider adaptation of this method. Proposed approach will provide POPE for building owners, managers, and building users for decision making.

2. Building rating methodology

Building performance is defined using qualitative and quantitative performance indices. Uncertainties are inherent in the performance evaluation of infrastructure systems. Due to the fuzziness of information, performance indicators of infrastructure systems can be estimated with different levels of certainty (most likely, minimum, and maximum). Benchmarks for infrastructure performance too are associated with significant uncertainties and subjectivity (e.g. LOS). Therefore, fuzzy synthetic evaluation (FSE) is used for the performance evaluation of building infrastructure. Ruparathna, et al. (2015) and Ruparatha et al (2017) have used FSE for LOS assessment of recreational centre buildings.

Performance assessment is a popular method used in building performance evaluation. However, data uncertainties and vagueness are some of the major challenges which make the building performance evaluation a demanding task. Input values of some performance indicators employed in this framework are inherently uncertain. In addition to accounting for these data uncertainties, incorporating qualitative inputs with quantitative data at the same time was required in determining the final performance rating. Probabilistic methods and fuzzy based approaches are commonly used to address these data uncertainties in literature. The probabilistic approaches are not well suited for this study, as the uncertainties associated with the input data are not statistical. Moreover, probabilistic approaches fail to deal with qualitative data. Therefore, Fuzzy set theory was chosen for this performance assessment framework considering its ability to account for data uncertainties and qualitative data simultaneously in determining the performance rating [22][23]. The

ability of fuzzy set theory to accommodate both numerical and non-numerical data by adopting linguistic terms, increases the flexibility and usability of the model [24][25].

In the field of engineering, Fuzzy set theory has become a popular application similar to many other fields such as data management, transportation, and logistics [4][7][26]. A fuzzy set can be mathematically represented as shown in the Equation 1 [9].

$$\tilde{A} = \{(x, \mu_{\tilde{A}}(x) | x \in X)\} \quad \text{Equation 1}$$

Where,

$\tilde{A}$ – Fuzzy set

X – Universal set

x – Objects of X

$\mu_{\tilde{A}}(x)$ – Membership function

In fuzzy set theory, a membership value in the range of 0 to 1 will be produced by the membership function to indicate the relationship between two parameters. A fuzzy set will be the collection of fuzzy values generated through the aforementioned methodology. In certain situations, deciding the exact state of a relationship is challenging. In these occasions, the state of a parameter can't be clearly categorized into one category. Therefore, fuzzy partial memberships are assigned to multiple performance levels. For example, if it is not possible to decide certainly whether the state of energy performance of a building falls under "good" or "very good" or "poor" category with the available data, it is possible to assign partial memberships to all related categories to indicate its true state, accounting for the uncertainty. Assigning memberships for multiple levels of a performance indicator as discussed above is a basic step of fuzzy synthetic evaluation (FSE). FSE aggregates multiple qualitative and quantitative input data to come up with a final score [31].

Four levels, namely "excellent", "good", "fair", and "poor" were considered for linguistic inputs in this study. Membership functions for each performance indicator were defined based on expert judgements and literature. Membership of each key performance criteria with the performance levels are compiled into a matrix (R). Inputs values for a given building will be compiled into a vector (w) based on the building performance level. These two parameters will be used to derive the fuzzy vector (e) for the building of interest, as shown in Equation 2 [9].

$$e = w \cdot R \quad \text{Equation 2}$$

Where,

e – fuzzy vector

w – input vector

R – fuzzy membership

Each performance criteria will have a fuzzy vector indicating its state. These fuzzy vectors will be aggregated with FSE to come up with an overall performance rating for a given building.

FSE based POPE method for MURB, as outlined below, involves four steps in calculating the performance of a public building [21][32]:

- i. Identification and classification of building performance indicators (BPI)s.
- ii. Fuzzification of the BPIs.
- iii. Aggregation of BPIs and LOS performance categories using FSE.
- iv. Defuzzification of the aggregated categories to calculate the total building performance.

2.1 Identification and classification of indicators

Indicator based systems have been commonly used in the literature to assess the sustainability performance of civil infrastructure. A comprehensive review was conducted to identify building operational performance indicators. Published literature and established building rating methods were used to identify performance indicators (Table 1). Table 2 presents the classified indicators according to the LOS categories. Published literature and expert opinion was used to develop this map.

Table 1: Building performance indicators (data obtained from Ruparathna et al (2017) [9])

Indicator	Reference
Availability of measures for protection against vandalism and security	[11]
User satisfaction level (Through a survey)	[33]
Indoor air quality (IAQ)	[6][33][34][35][36][37][38]
Thermal comfort to the users	[34][33][36][39][40]
Building cleanliness and visual comfort to the users	[35][33][37][37][38] [36]
Indoor noise level	[33][34][39][41][42]
Indoor luminance level	[6][33][35][37][38]
Adequacy of building amenities to users	[43]
Condition rating of building equipment	[11][36][37][38]
Access to services in normal and emergency conditions	[11]
Number of deaths, injuries and illnesses while using assets or services	[11]
Non planned service interruptions as a % to planned service interruptions	[11][44]
Number of user days with no service interruptions	[11][44]
Quality of swimming pool water	[38]
Annual energy use intensity (GJ/m ²)	[34][36][45][46][47][48][49]
Annual renewable energy consumption (% the total energy)	[6][34][35][36][37][38]
Annual GHG emission reduction	[33][34][36][37][46][48][49]
Annual water consumption per user	[34][36][45][48][49]
Amount of water recycled as a % to waste water	[33][34][37]
Average cost of operation as a percentage of annual income	[33]
Amenities for persons with disability	[6][34]
Cycling convenience for the users	[36]

2.2 Fuzzification of the Performance Indicators

In order to establish LOS, MURB owners, strata managers should establish predefined targets and performance levels [50]. These targets would be used as benchmarks for performance assessment. Both standard benchmarks and manager defined benchmarks are proposed.

Fuzzy set for PIs was developed based on its association to the performance benchmarks [24][32] [51]. Benchmarks defined by building owners and literature are presented in Appendix A. Same benchmarks were used to generate fuzzy sets. Each

PI is expressed as a pentaduple fuzzy number (PFN). Performance level associated BPIs can be in multiple forms, monitored crisp value (i.e. energy demand: 8000 GJ/year), monitored uncertain value (i.e. building asset condition rating: 5-7), and qualitative value (i.e. building cleanliness and visual comfort: good). Highest membership value for performance level was selected for multiple intersections. Pseudo numeric values were used to fuzzify and plot qualitative fuzzy numbers [24].

2.3 Aggregation of indicators and categories

The aggregation operation involves of combining PIs level performances to upper levels (i.e. performance category (PC) and building). PFN of BPis were aggregated to calculate the performance related to PCs by using the indicator map in Table 2. Weighted

sum method was used for aggregation. LOS performance categories were aggregated to calculate the LOS of the overall building. Weighted sum method was used to aggregate BPis and PCs. Weights were defined according to the priorities of the institution.

Table 2: Classification of LOS indicators for buildings adopted from Ruparathna et al. (2017) [9]

Building Performance Indicator (BPI)	Performance categories (PC)								
	Safety	Quality	Quantity	Capacity	Reliability	Responsiveness	Environmental acceptability	Cost	Availability
Availability of measures for protection against vandalism and security	✓								
User satisfaction level	✓	✓	✓	✓	✓	✓	✓	✓	✓
Indoor air quality (IAQ)	✓								
Thermal comfort to the users		✓					✓		
Building cleanliness and visual comfort to the users		✓				✓			
Indoor noise level		✓					✓		
Indoor luminance level		✓							
Adequacy of building amenities to users		✓		✓					
Condition rating of building equipment				✓	✓				
Access to services in normal and emergency conditions					✓				
Number of deaths, injuries and illnesses while using assets or services	✓				✓				
Non planned service interruptions as a percentage to planned service interruptions					✓	✓			
Number of user days with no service interruptions					✓	✓			
Quality of swimming pool water		✓					✓		
Annual energy use intensity (GJ/m ²)							✓	✓	
Annual renewable energy consumption (As a proportion of the total energy)							✓		
Annual GHG emission reduction							✓		
Annual water consumption per user							✓		
Amount of water recycled as a % to waste water							✓		
Average cost of operation as a percentage of annual income								✓	
Amenities for persons with disability		✓							✓
Cycling convenience for the users		✓					✓		

2.4 Defuzzification of the Aggregated Indexes

PFN calculated for PC and the building would be defuzzified to obtain a crisp number. The centroid method would be used for defuzzification. Overall LOS index is calculated using Equation 3 [9].

$$LOSI = D_1 C^T \quad \text{Equation 3}$$

Where,

C^T - Transpose of a vector of centroid values of the membership functions

D - Performance of a category/building

LOSI - index value for the performance category and the MURB.

3. Overview of the tool

The above methodology was developed as a web based tool LOS assessment of MURB. The LOS tool will be accessed via a login page. Users can register and login in to the system using their email (Fig 1).



Fig 1: Login page

Fig 2. illustrates the input screen of the tool. Performance related to various parameters can be inserted as a range. Results will be displayed as a radar diagram. A pseudo result is depicted in Fig 2. The result provides a detailed breakdown of the service provided by the building into different LOS categories.

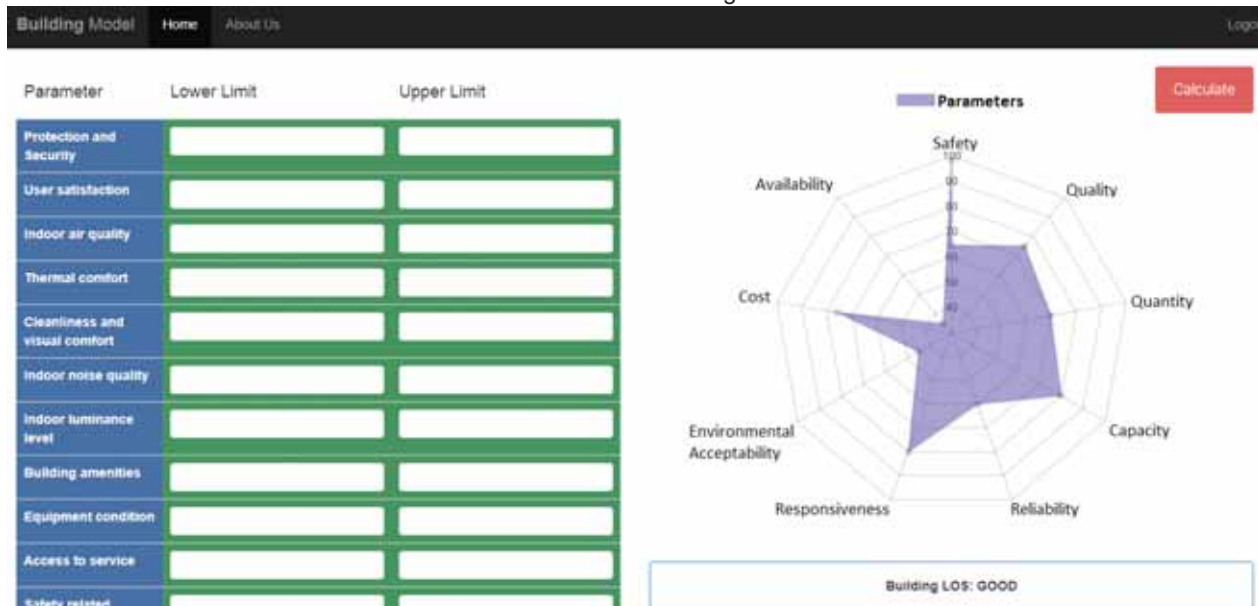


Fig 2: Input and results page

4. Results and discussion

Commonly used POPE methods provide a snap shot view, without providing adequate information to manage the operational performance. LOS could be a versatile approach to manage the post occupancy performance of MURB. The proposed tool is an extension of the building LOS assessment method proposed by Ruparathna et al. (2017). This will provide an indication of the operational performance in the building and service received by the tenants.

LOS based performance assessment is a multi-faced evaluation approach that combines asset management, build operational rating, and facilities management. This will provide holistic view on the operational performance of a building. Tool will provide a detailed evaluation of the service provided

in terms of safety, customer satisfaction, quality, quantity, capacity, reliability, responsiveness, environmental acceptability, cost, and availability. Furthermore, this information will be combined to conduct an overall evaluation of the building. Performance targets could be established for each BPI.

FSE based method enables the use of incomplete, qualitative and vague data in the evaluation. POPE should be conducted using both qualitative and quantitative performance indices. Uncertainties are inherent in the performance evaluation of infrastructure. Due to the fuzziness of information, performance related to indicators can be estimated with different degrees of certainty (most likely, minimum and maximum). Moreover, benchmarks for building performance are allied with uncertainties and

subjectivity. Therefore, FSE was the best method for operational performance evaluation in the given context.

Proposed tool is a self-evaluation tool for MURB. Overall assessment of the building (i.e. entire building and category performance) can be influenced by pre-established performance benchmarks and category weights. The tool can be customized according to organizational priorities by altering the benchmarks. The building owner or the strata managers could define the benchmarks for the LOS. This is one of the unique features of the proposed approach. Post occupancy performance targets related to several categories should be defined by the organization. The MURB management organization, should establish constructive performance benchmarks related to above categories as a responsible citizen. Updating benchmarks could continuously improve the service provided by the MURB.

Safe and healthy housing is important for tenants. Building owners and managers should be committed to support sustainability targets of the region and country. The proposed tool will provide information with regards to both categories. By making LOS performance data available, tenants can make informed decisions on selection of MURB. Furthermore, tenants will be aware of the status of ongoing facilities management operations at the MURB.

Web-based platform will enhance the adaptation of this tool. This information would enable organizations such as BC housing to create a comprehensive database on the operational performance on the MURB. This information would assist in developing new initiatives (i.e. grant programs, laws) to enhance the services to tenants.

5. Conclusions and outlook

The proposed tool is an objective method for post-occupancy performance evaluation. Proposed level of service based approach addresses a number of inadequacies of popular building performance evaluation methods. This approach would assist owners, strata managers and tenants in managing and monitoring operational performance of MURB.

Two potential research studies could extend the capabilities of the proposed tool. First, the proposed approach can be customized to suit the various geographical constraints and organizational contexts. This can be achieved by changing the indicators and benchmarks. This approach provided three levels of detail for operational management of MURB that will inform building owner, strata managers, and tenants. Second, the web-based tool is aimed at improving service provided by MURB. Hence, further research is required to assess the industry requirements and challenges for implementing similar approaches in the housing industry.

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Appendix A: Benchmarks adopted from Ruparathna et al (2017)

Indicator	Data Source	Benchmark	Performance levels				
			Very High	High	Moderate	Low	Very Low
Availability of measures for protection against vandalism and security	Qualitative / Observation	Manager/owner defined	State of the art security features are installed (e.g. sensors) , building is continuously monitored and security service is stationed at the facility	building is continuously monitored and security service conducts routine patrols	Security service is contracted and they conduct routine patrols	Building is monitored using CCTV	No security measures are in place
User satisfaction level	Through a survey	Manager/owner defined	Very Satisfied	Satisfied	Neutral	Dissatisfied	Very Dissatisfied
Indoor air quality (IAQ)	Measured (mg/m ³)	Literature [52]	0<0.2		0.2-0.3	0.3<	
Thermal comfort to the residents	Measured (°C)	Manager/owner defined	25-26		22-24		<22 & >26
Building cleanliness and visual comfort to the residents	Through a survey	Manager/owner defined	Excellent	Good	Moderate	Bad	Very bad
Indoor noise level	Measured (dB(A))	NRC [53]	>40		40-45	45<	
luminance level in common areas	Measured (Lumens/Square Meter)	U.S. General Services Administration [54]	>750		500-750	500>	
Adequacy of building amenities to residents	Through a survey	Manager/owner defined	Very Satisfied	Satisfied	Neutral	Dissatisfied	Very Dissatisfied
Condition rating of building equipment	Expert judgement	Manager/owner defined	Excellent	Good	Fair	About to fail	Failed
Access to services in normal and emergency conditions	Expert judgement	Canadian Centre for Occupational Health & Safety, Emergency Planning [55]	Emergency preparedness plan is established and regular drills are conducted	Emergency preparedness plan is established and regular drills are conducted	Emergency preparedness plan is available	Standard safety and emergency plans are available	No emergency response procedures
Number of deaths, injuries and illnesses while using the facility due to an accidents in common areas	Daily logs	Manager/owner defined	0-2	1-3	2-4	3-5	5<
Non planned service interruptions as a percentage to planned service interruptions	Daily logs (Percentage)	Manager/owner defined	0-2%	1-3%	2-4%	3-5%	5%<
Number of days with no service interruptions	Daily logs	Manager/owner defined	0-2	1-3	2-4	3-5	5<
Quality of water	Monitored information	BC Ministry of Health [56]	Chemical parameters are maintained in the specified range and no health concerns are reported	Chemical characteristics of water is maintained between BC approved water quality guidelines	Chemical parameters slightly deviate from the specified range	Chemical parameters significantly deviate from the specified range	Chemical parameters significantly deviate from the specified range and health problems are reported

Annual energy use intensity (GJ/m^2)	Monitored information (GJ/m^2)	CIBSE [57]	<725	725-1573	1149-1997	1573-1997	1785
Annual renewable energy consumption (As a proportion of the total energy)	Monitored information (As proportion of total energy)	LEED [58]	>12%	12-7.5%	9-6%	6-3	3%>
Annual GHG emission reduction	Calculated using energy demand (Percentage of GHG emission reduction from the previous year)	Manager/owner defined	>33%	33%-20%	20%-0	0	Increase
Annual water consumption per resident	Monitored information ($\text{m}^3/\text{user/annum}$)	CIRIA [59]	<60	60-130	95-175	130-220	220<
Amount of water recycled as a % to waste water	Monitored information (Percentage of waste water recycled)	LEED [58]	<1%	1-2%	1-3%	2-4%	4%<
Average cost of operation as a percentage of annual income	Calculated data from P&L	Manager/owner defined	>0		0	0<	
Amenities for residents with disability	Monitored information	United Nations [60]	Standard facilities are available for disabled workers and visitors. Multiple entrances are available, All building amenities are accessible.	Standard facilities are available for disabled workers and visitors. Multiple entrances are available.	Standard amenities are available in a disabled workers and visitors. Entrance via main entrance	Building can be accessed by a wheelchair user via alternative entrance	Limited amenities are available for disabled.
Cycling convenience for the residents and visitors	Monitored information	City of Nelson [61]	Bicycle parking lockers are available for within 15m of the entrance. Bicycle parking is well lit, visible to visitors and separated from car parking	Bicycle parking is within 15m to the main entrance and separated from car parking.	Bicycle parking is available in a side of the building and is separated from car parking.	Bicycle parking is not separated from car parking available at a side of the building.	No parking facilities for cyclists

Comparative Analysis of Environmental Product Declarations on Building Materials – Softwood Lumbers under Different Product Category Rules

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Abstract:

Building sector has consumed over 40% of the total energy in the European Union and United States. The upward trend in environmental impacts of buildings will continue in the future due to the growth in population, longer hours spent inside buildings, and increasing demand for building services and occupants' comfort. Due to the above concerns, reducing the environmental impacts of buildings and building materials becomes significant. One of the most recommended methods to report on the environmental impacts of building materials is the standardised Environmental Product Declaration (EPD). EPD provides verified and quantified environmental information over the life cycle of goods or services based on ISO 14040 and ISO 14044 standards. EPD must be conducted under Product Category Rules (PCRs) which define specific agreed guidelines for each product category.

This paper discusses the EPD processes and guidelines of building materials in different countries. The life cycle assessment (LCA) stages for different EPD systems were analyzed, and the environmental impacts, resource uses, and waste disposals of building materials were studied. The comparable analysis was conducted for EPDs of softwood lumbers from different continents, and the results showed that it is not feasible to compare EPD outputs that are from different declaration guidelines. The harmonisation of declaration rules is vital in order to communicate the EPDs of building materials among different countries and reduce the total environmental impacts on building sector. The new declaration rules considering the full LCA stages from cradle to grave should be developed through future research.

Keywords:

Environmental Product Declaration, LCA, Building Materials, Environmental Impacts

Table of Abbreviation

ADP	Abiotic Depletion Potential
AWC	American Wood Council
DOCf	Degradable Organic Carbon Fraction
EPD	Environmental Product Declaration
GHG	Green House Emissions
PCRs	Product Category rules
ISO	International Standard Organization
IBU	Institut Bauen und Umwelt e.V.
LCA	Life Cycle Assessment
NGA	National Greenhouse Accounts
NHWD	Non Hazardous Solid Waste
RSF	Renewable Secondary Fuels

1. Introduction

Presently, the world is facing critical environmental problems such as global warming, ozone layer depletion, increasing waste accumulation, etc. [1]. The building sector has a significant impact on these environmental problems as it accounts for about a third of greenhouse gas (GHG) emissions [2][3]. Numerous initiatives have been taken all around the world to enhance building sustainability performance and reduce the environmental impacts. Environmental Product Declaration (EPD) of a building is one of the most recommended method to report on the environmental impacts of building materials [4].

An EPD provides quantified and independently verified environmental information considering the life cycle of goods or services with ISO 14040 and ISO 14044 standards [5]. EPD labels provides transparent environmental information through LCA which will increase the positive market feedbacks [6]. EPD indicators include: environmental impacts, resource use, waste categories and output flows leaving the system [7]. The EPD for an entire building was first developed in Sweden under the International EPD System. One of the goals of EPD is to help reduce the impact on climate from the construction sector by encouraging planners and designers to use the LCA in building planning and design [8].

EPDs are being developed worldwide either by independent organizations or within highly organized frameworks since the launch of the first scheme in 1998 [9]. However, the rules applied to develop EPD certificates vary from different organizations. This study will analyze three EPD certificates for the same type of building materials from different continents, compare the similarities and differences of the EPD certificates, and propose a standardized methodology to harmonize declaration results for global improvement.

2. Background

The International Standards Organisation developed a package of standards, as part of ISO 14000 series environmental standards, on environmental labeling which covers three types: Type I Environmental label describes the product's or services' impacts on the environment and its acquisition is based on voluntary action [10]. Type II Environmental label consists of companies' and organisations' self-declared environmental claims without verification by any third party [11]. Type III Environmental label is also called Environmental Product Declaration (EPD). It provides quantified environmental information which is independently verified by a third party over the life cycle of a specific product [12].

The international EPD system, launched in 1999, was the first EPD programme to be developed on a worldwide scale, and the most commonly implemented one in Europe [13]. In 2000, the Institute for Environmental Research and Education founded Earthsure in United States, which becomes the first EPD program in North America [14]. As more EPD programs were established, EPDs are becoming more and more famous and operational on the market due to its ability to communicate comparable and credible information relating to environmental performance of products [15].

The quantified environmental information and impact categories of EPDs are based on the LCA methodologies according to the ISO14040 (2006) series of standards. In the international standard, EPDs are primarily designed to use in business-to-business (BtoB) communication, but there may be EPDs used to provide quantitative and detailed data in business-to-customer (BtoC) communication [12]. In BtoB EPD, the system boundary of LCA information starts from raw material extraction process to the end of manufacturing process, and the EPD itself does not need to be verified by third-party. In BtoC EPDs, the system boundary of LCA information starts from raw material extraction to the final disposal after use. BtoC EPSs must be third-party verified [16].

In order to facilitate environmental comparisons between products that perform the same function, EPD must be directed under specific agreed guidelines for each product category known as Product Category Rules (PCRs) [17]. PCRs identify

the scope and goal of the LCA-based information for the product category and the guidelines on creating the additional environmental information for the product category. PCRs also specify the parameters, the included life cycle stages, and information that must be collated and reported in the EPD. Program operators oversee the PCR development, and provide detailed guidelines for developing PCRs and EPDs. [12].

Since PCRs are usually set in a way that allows the program operator to interpret the rules in different ways, which leads to the potential incomparability of EPDs on the same PCRs [18]. In order to practically compare products using EPDs, harmonization of their development among programmers is needed [19]. Although there are a few guidelines that start to promote the global consistency, there is still a big knowledge gap for the declaration methods and guidelines in different countries. By comparing the EPD reports from different countries, the countries that are in the starting stages of EPD development can achieve valuable information from other countries. In this studies, three EPDs from different continents will be deep analyzed and compared. The similarities and differences of the three EPDs will be pointed out. The advantages and drawbacks of each EPD declaration method will be discussed. The conclusions will be summarised based on the comparison results, and suggestion will be proposed for further EPD harmonization.

3. Methodology

In order to show the differences and similarities of EPDs from program operators around the world, the EPDs of the most commonly used building material softwood lumber were selected in this study. The softwood lumbers from Europe, North America and Australia were selected, and the detailed EPD information and building material information are listed in Table 1&2.

Table 1: General EPD information of softwood lumbers from different program operators.

	EPD - IBU	EPD - AWC	EPD-Australia
Program Operator	Institut Bauen und Umwelt e.V. (IBU)	UL Environnent	The Australasian EPD Program Ltd
Declaration Holder	Fritz EGGER GmbH & Co. OG	American Wood Council & Canadian Wood Council	Forest and Wood Products Australia Ltd (FWPA)
Declared Unit	1m ³ EGGER sawn timber dried	1m ³ planed, kiln-dried softwood lumber	1m ³ sawn kiln-dried softwood lumber
Issued Date	08-Apr-16	16-Apr-13	13-Jul-15
Valid to	07-Apr-17	15-Apr-18	22-Jun-20
Source	https://epd-online.com/PublichedEpd/Detail/7905	http://www.awc.org/greenbuilding/epd	http://www.environdec.com/en/Detail/epd560
PCR Referenced Standard	ISO 14025 & EN 15804	ISO 14025 & ISO 21930	ISO 14025 & EN 15804
PCR	Solid Wood	FPInnovations:	PCR 2012:01

	Product, 07, 2014	2011. Product Category Rules (PCR) for preparing EPD	Construction products and Construction services, Version 2.0, 2015-03-03	mentioned in the EPD-AWC report that the system boundary begins with forest management and resource extraction, and ends with planed dry lumber ready for shipment at the manufacturer. Therefore, EPD-AWC is the “cradle to gate” Type with the product stage declared in the report. The detailed information of each module for the system boundary was summarized and listed in Table 3.
PCR Reviewer	Independent Committee of Experts (SVA)	FPIInnovation	The Technical Committee of the International EPD System	
Independent Verifier	Appointed by SVA Advisory Board	Industrial Ecology Consultants	Catalyst Ltd	

Table 2: The detailed information of the building materials - softwood lumbers.

	EPD - IBU	EPD - AWC	EPD-Australia
Wood Type	Spruce/Pine	Pine/Fir/Cedar	Pine
Wood Moisture	15%	12%	12%
Dry Density	507 kg/m3	434 kg/m3	550kg/m3
Production Site	Brilon Germany	North America	Australia
Product Description	The timber is made of fresh spruce or pine logs without using excipients and additives. The declared product is delivered at the production site in Brilon	The kiln-dried and planed softwood lumber is available in a range of nominal dimension. The size of 2x4 and 2x6 is chosen for the LCA analysis	Seasoned sawn softwood analyzed in this document is untreated softwood only. This EPD documents can be used by project teams to obtain points for Green Star rating tools
Source	https://epd-online.com/PublishedEpd/Detail/7905	http://www.awc.org/greenbuilding/epd	http://www.environmentaldec.com/en/Detail/epd560

System Boundaries for LCA Calculation

There are three types of EPDs based on the difference of system boundaries: Cradle to gate, cradle to gate with options and cradle to grave. Cradle to gate EPD only cover the product manufacturing stage. Cradle to gate with options EPD covers the product manufacturing stage, and any other information that might be important to report in the usage stage or disposal stage. Cradle to grave EPD covers all of the life cycle stages as a minimum, and some benefits over system boundary may be included. Only Cradle to grave EPD can be applied to comparison if the functional unit is equivalent [21].

EPD-IBU and EPD-Australia are both the “cradle to gate” Type with options based on the EN 15804 standard. The product stage, which includes: 1) Raw material supply, 2) Transport of raw materials and 3) Manufacturing, was declared by EPD-IBU and EPD-Australia. In terms of the optional stages, only the reuse/recovery/recycling potential was declared by EPD-IBU, while the waste processing and disposal stages were also declared by EPD-Australia beside the Module D.

In respect of the EPD-AWC, the EN 15804 standard was not applied to the report. The system boundary format for EPD-AWC was not the same as the format of EPD-IBU or EPD-Australia. However, it was

Data Acquisition and Calculation

The original data for each LCA sub-stages that are included in this LCA boundary are derived from the three EPD reports: EPD-IBU, EPD-AWC, and EPD-Australia. The sources of these EPD reports are listed in Table 2. The LCA assembly for each soft lumber will be developed based on the manufacturing techniques. Assumptions and cut-offs will be applied to each LCA based on the allowance from EN15804 standards.

In terms of the LCA analysis, the advance software GaBi was adapted in this research. GaBi is a product system modeling and assessment software that first appeared on the market in 1992, developed and distributed worldwide by PE International. GaBi has an important LCA database which supports several life cycle impact assessment methodologies [22]. GaBi 6 database 2013 was adapted by EPD-IBU, and Gabi 6 database 2014 was adapted by EPD-Australia.

4. Results and discussions

Based on the input data described above, the LCA output of each EPD was created and shown in Table 4.

Validity Period

As shown in Table 1, the validity of EPD-AWC and EPD-Australia is 5 years, EPD-Australia and EPD-IBU both follow the EN 15804 standards. Therefore, the valid period is set at 5 years. However, the validity of EPD-IBU is only 1 year. Because the PCR document of EPD-IBU has additional requirement for the period of EPD. In Section 7: Requisite Evidence of the EPD-IBU PCR document, statements of Formaldehyde, MDI, Fire gas toxicity and VOC emissions must be documented if relevant to the scope of the product. The VOC verification could be optional if the EPD is only valid for 1 year. Since the VOC emissions was not specified in the EPD-IBU, the validity of this EPD was set to 1 year [23]. The PCR for EPD-Australia also has additional requirement for the validity of the EPD. It is stated that the surveillance follow-up shall be conducted by monitoring the main parameters during the validity period to evaluate if the contents are still consistent with the current situation [24].

PCR Reference Standards

The EPD development is based on the specific PCR document that describes scope and goal of the LCA analysis and specify the parameters to be covered. In

order to analyze the differences of LCA results for the three EPDs, the general information of the PCRs for these three EPDs shall be analyzed.

As shown in Table 1, three EPDs all comply with ISO 14025, which specifies the principal and general procedure to develop an EPD document. The harmonization of the program instructions and PCR between different program operators are encouraged by ISO 14025 to meet the principal of comparability [12]. That is the initial principal of EN 15804 Core-PCR to create the harmonization for construction materials. EPD-IBU and EPD-Australia were developed in appliance with EN 15804, while EPD-AWC only complied with ISO 21930 which describe the principal and framework for environmental declaration of building products. EN 15804 was prepared in conformity with ISO 21930, which has more specified requirement for EPD development than ISO 21930 (CEN 2013; ISO21930 2007).

Due to the different PCR reference standards for the three EPDs described above, it is clear that the LCA results shown in Table 4 between EPD-IBU and EPD-Australia are comparable with each other but not comparable with EPD-AWC.

Declared Unit

As shown in Table 2, the declared unit of EPD-IBU is 1 m³ of EGGER sawn timber dried with the average density of 507 kg/m³, which represents the wood product from EGGER sawmill in Brilon. The declared unit of EPD-AWC is 1 m³ of planed, kiln dried with the average density of 434 kg/m³, which represent the whole North American Softwood lumber. The declared unit of EPD-Australia is 1 m³ of sawn kiln-dried softwood with the average density of 550 kg/m³, which represents the Australian native and exotic softwood species. The declared units for EPD-AWC and EPD-Australia represent an entire product category, while EPD-IBU represents a specific product from a specific manufacturer. Therefore, a specific product purchased on North American and Australian markets might have a less or greater environmental impact than the average results presented by EPD-AWC and EPD-Australia. Any specific manufacturers from EPD-AWC and EPD-Australia shall create their own EPDs if more accurate environmental impact is needed.

In terms of the type of softwood species, the three EPDs have varieties of types and all of them are common for softwood lumber. The timber products from EGGER sawmill for EPD-IBU are spruce wood or pine wood. The dominant softwood species for EPD-AWC are pines, firs and red cedar [26]. The common softwood species for EPD-Australia are different type of pines, such as radiate pine, hoop pine, etc. The variety in softwood species does not have impact on the comparison of the LCA results as

long as the system boundaries are clearly defined and compared.

System Boundary

The detailed system boundary for each module was clearly described in Table 3. The product stage was declared by all of the three EPDs which is mandatory based on the requirements of EN 15804. For the cradle to gate EPDs, the comparison between the three EPDs will be mainly focused on the results from product stage. In regards to the additional modules, such as module C3, C4 and D, declared by EPD-IBU and EPD-Australia, the results from these modules are presented for users to better understand the environmental performance of the product from its whole life span.

In Table 3, the partial process of raw material supply (A1) was the same for EPD-AWC, EPD-IPU and EPD-Australia which is the basic steps for forestry operation. In terms of transportation (A2), only the liquid fuel was involved as input, which is the same for all the three EPDs. Therefore, the further distance between the logging site and the manufacturer factory, the higher environmental impact it will be created. In the manufacturing stage (A3), the processes to produce lumbers are similar among the three EPDs. The LCA outputs from the Product Stage (A1-A3) can be used to represent the environmental performance of the three EPDs.

In terms of the reuse/recovery/recycling potential, EPD-IBU stated that the EGGER timber at the end of life stage will be used for biomass incineration to create thermal and electrical energy. The timber for EPD-Australia at end of life stage will have two options: waste processing and disposal. In the waste processing stage, the wood waste can be shredded and combusted for energy recovery or recycled to create woodchips. In the disposal stage, the wood waste will be landfilled to create gas energy. Depending on the different value of degradable organic carbon fraction (DOC_f) of the wood, the landfill has two scenarios: the typical scenario with DOC_f equals to 0.1%, the NGA scenario with DOC_f equals to 23% which was chosen for Australia's National Greenhouse Accounts (NGA). Both of the scenarios are based on the output from bioreactor laboratory research.

Lifecycle Assessment Results

The outputs for the three EPDs are listed in Table 4. In terms of the Environmental Impacts, EPD-AWC declared five parameters for the environmental impact, while EPD-IBU and EPD-Australia declared seven parameters. EPD-AWC has different unit from the other two EPDs for the Acidification Potential parameter, EPD-AWC is also the only one that has the Smog Potential parameter. In regards to the value of the EPDs, EPD-AWC has a much lower value for

Table 3: Detailed system boundary of three EPDs for softwood lumbers.

LCA Stage		EPD - IBU	EPD - AWC	EPD- Australia
Product Stage	A1: Raw Material Supply	1. Procurement and processing of raw materials	1. Forest Management	1. Seeding production and planting
		2. Processing of secondary raw materials	2. Logging	2. Forest residue burning
			3. Planting	3. Monitoring, fire prevention and control
			4. Log Packaging	4. Road building
	A2: Transportation	Transportation to the manufacturer	Transportation to the log yard	5. Log harvesting
				Log transport
	A3: Manufacturing	1. Log sorting	1. Log sorting	1. Log storage
		2. Debarking	2. Debarking	2. Debarking
		3. Machining, profiling, sawing	3. Sawing, machining	3. Sawmilling
		4. Timber	4. Kiln drying	4. Kiln drying
		5. Packaging	5. Planning	5. Planning
		6. Technical drying	6. Softwood lumber packaging	6. Packaging
End-of-life	C3: Waste Processing			1. Shredding and combustion for energy recovery
				2. Wood waste recycling for woodchips
	C4: Disposal			Landfill for gas energy recovery
Benefits over system boundary	D: Reuse/Recovery/ Recycling Potential	Biomass incineration for thermal and electrical energy production		Potentials of C3 +C4

Table 4: LCA results for three EPDs of softwood lumbers.

Parameter	Unit	EPD-IBU		EPD-AWC			EPD-Australia				
		A1-A3	D	A1-A3	Forestry Operation (A1)	Lumber Production(A2+A3)	A1-A3	C4 Landfill (Typical)	C4 Landfill (NGA)	C3 Energy recovery	C3 Recycling
Environmental Impacts											
GWP*	kg CO2 eq.	-784.0	-603.0	-72.6	-10.56	-62.09	-689.0	61.20	749.00	906.00	906.00
ODP	kgCFC11eq.	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
AP	kg SO2 eq.	0.24	-0.27				1.05	0.18	0.23	0.89	0.04
	H+moles eq.			42.3	5.43	36.82					
EP	kg(PO4)3- eq.	0.05	0.00	0.03	0.01	0.02	0.31	0.02	0.03	0.18	0.01
POCP	kg C2H4 eq.	0.08	0.03				0.58	0.02	0.15	0.10	0.00
ADP-elements	kg Sb eq.	0.00	0.00				0.00	0.00	0.00	0.00	0.00
ADP-fossil fuels	MJ	318.0	-5340				2450	842.0	842.00	72.40	72.40
Smog Potential	kg O3 eq.			14.5	2.84	11.67					
Resource use											
PERE	MJ	1330	IND				2600	42.10	42.10	9290.0	1.77
PERM	MJ	8160	IND				9290	0.00	0.00	-9290.0	-9290.0
PERT	MJ	9490	-829.0				11900	42.10	42.10	1.77	-9290.0
PENRE	MJ	330.0	IND				2460	861.00	861.00	72.40	72.40
PENRM	MJ	0.00	IND				0.00	0.00	0.00	0.00	0.00
PENRT	MJ	330.0	-6990.0				2460.	861.00	861.00	72.40	72.40
SM	kg	0.00	0.00				0.00	0.00	0.00	0.00	0.00
RSF	MJ	1610	8160.0				0.00	0.00	0.00	0.00	0.00
NRSF	MJ	0.00	0.00				0.00	0.00	0.00	0.00	0.00
FW*	m3	-1.59	-1.59	0.09	0.01	0.08	325.0	0.25	0.32	0.61	0.03
Non-renewable fossil	MJ			1113.01	156.99	956.02					
Non-renewable nuclear	MJ			114.48	1.60	112.88					
Renewable, biomass	MJ			1578.86	0.00	1578.86					
Renewable, other	MJ			60.6	0.27	60.33					
Non-renewable material	Kg			0.11	0.00	0.11					
Renewable material	Kg			468.11	0.00	468.11					
Waste to disposal											
HWD	kg	0.01	-0.60				0.00	0.00	0.00	0.00	0.00
NHWD	kg	2.01	4.58	15.0	0.10	14.89	54.20	552.00	350.00	0.00	0.00
RWD	kg	0.00	-0.63				0.01	0.01	0.01	0.00	0.00
Other output flows											
CRU	kg	0.00	IND				0.00	0.00	0.00	0.00	0.00
MFR	kg	0.00	IND				0.00	0.00	0.00	0.00	550.00
MER	kg	IND	IND				0.00	0.00	0.00	0.00	0.00
EEE	MJ	IND	IND				0.00	0.80	185.00	3040.0	0.00
EET	MJ	IND	IND				0.00	0.00	0.00	3040.0	0.00

Global Warming Potential, which is only around 10% of the values for the other Two EPDs. Due to the difference in PCR reference standard, the comparison between EPD-AWC and the other two EPDs is unrealistic.

In terms of the resource use, the parameters of EPD-AWC are totally different from the parameters of EPD-IBU and EPD-Australia, which makes it unfeasible to conduct the comparison. With respect to the values for Waste Disposal and Other output flows, it was not declared by EPD-AWC, only the value of Non Hazardous Solid Waste (NHWd) was stated by EPD-AWC as part of the LCA results. The NHWD results for EPD-AWC is higher than EPD-IBU and much lower than EPD-Australia.

It is much easier to compare the LCA results between the EPD-IBU and EPD-Australia since both of them comply with the same PCR reference standard. As per the environmental impacts results shown in Table 4, the parameters of ODP and ADP-elements are both close to 0, and the values of GWP, AP, EP and POCP from EPD-Australia are slightly higher than the values from EPD-IBU. In regards to the Abiotic Depletion Potential (ADP)-fossil fuels, value from EPD-IBU is more than seven times lower than EPD-Australia. Based on the Product Stage comparison (A1-A3) for the two EPDs, EPD-IBU has better environmental performance than EPD-Australia.

In regards to the Resource use between EPD-IBU and EPD-Australia, the values of nine parameters from EPD-Australia are higher than the corresponding values from EPD-IBU. The only difference is the parameter of Renewable Secondary Fuels (RSF), 1610MJ RSF energy resource was used by EPD-IBU, and nothing was consumed by EPD-Australia. The total energy consumed from the eight parameters by EPD-IBU and EPD-Australia are 21250MJ and 28710MJ respectively. Therefore, EPD-IBU has a better performance than EPD-Australia in Resource use as well.

It is shown in Table 4 that EPD-IBU has a better performance than EPD-Australia in terms of environmental impacts and resource use. It might be that the impact of transportation (A2) for Germany is lower than Australia because there is a closer distance between the logging plant and sawmill in Germany. However, the LCA output for the product stage (A1-A3) was combined into one result instead of three separate results, so it is not possible to analyze which part of the product stage has a less environmental performance. The LCA results for the product stage from EPD-AWC are more specific than EPD-IBU and EPD-Australia, as the separate results were calculated for the two partial steps of the product stage: Forestry Operation and Softwood Production. The results for the transportation module defined in EN 15804 standard was combined into the softwood production step. Based on the LCA results from forestry operation step and softwood production

stage, it is concluded that softwood production is the primary driver of the environmental impact and resource use which consumes 86% of fossil fuel and 100% biomass energy.

If the LCA results for the product stage could be separated with three results for Raw Material Supply, Transportation and Manufacturing respectively. The comparison between different EPD could be more specific, and the comparison output would be more beneficial for EPD owners to improve the environmental performance of their products.

Since the results of EPD-AWC and EPD-Australia represents the entire product category of their nation, the regional factor was considered when conducting the LCA analysis. The LCA results of EPD-AWC represent the five different LCA studies from one Canadian average study and four U.S manufacturing regions by putting different weight on each study. The weights signed to each manufacturing region is based on the relative annual production. The LCA results for EPD-Australia is based on four case studies spanning five states that cover 50% of the Australian production. All electricity and thermal energy inputs for EPD-Australia are also based on the Australia average rather than state-specific energy mixes. However, The LCA results for EPD-IBU only represents the average environmental performance of the softwood at the production site in Brilon. Therefore, the LCA results of EPD-IBU is more specific compared with the other two EPDs.

Cut-off Criteria

The cut-off criteria should be defined in case of data gaps or insufficient data for a unit process, and it has impact on the system boundaries. It is stated in EN 15804 that the mass of a unit process in the cut-off criteria shouldn't be over 1% of the total mass input. The total input flows per module in the cut-off criteria could reach the maximum 5% of mass and energy usage except that the input flow has significant effects in their extraction, use, or disposal stage or the input flows are classified as hazardous waste [21].

In the cut-off criteria for EPD-IBU, only color ink rollers for the labels and staples for attaching packaging materials to the product were not covered. The cut-off criteria for EPD-IBU stated that a flow may be excluded if it is less than 1% of the cumulative mass of the model flows or the cumulative energy of the system model. Machinery, facilities and infrastructure required in manufacturing are not considered into the EPD-IBU system boundary as well. The cut-off criteria for EPD-Australia stated that the environmental impacts relating to infrastructure, product equipment not directly consumed in the process, and personnel are not included, and the impact of packaging is also excluded. By comparing the cut-off criteria for the three EPDs, it is concluded that all the major flows that have large or small impacts to the LCA output are well analyzed into the system boundary.

Software used for LCA

The software used for LCA analysis is important for the EPD comparisons. As described above, GaBi software was applied to the LCA developments of EPD-IBU and EPD-Australia, while Athena software was applied to the LCA development of EPD-AWC. There are EPDs developed all around the world, and the LCA results could be generated by all kinds of software. It is possible that different outputs could be generated by different software even though the inputs are the same. On the other hand, due to the limit of database, the assumptions made based on different database might not be the same as well. Therefore, in order to increase the comparability of EPD results, the database from different software should be regulated.

Necessity for EPD Comparison and Harmonization

The purpose of EPD document is to communicate comparable information about the lifecycle environmental impact of products. However, if the reference standards of the EPDs are not the same, it is not feasible to conduct the comparison. Such as the comparison between EPD-AWC and EPD-IBU, which does not have the same output parameters for LCA results. Therefore, the harmonization of EPDs between different program operators becomes significant. In Europe, the ECO Platform EPD was developed to guarantee the consistency to the assessment of construction works and achieve European consensus on communicating environmental information. EPDs from ECO Platform provide the required information in a standardised format to avoid inconsistencies between different assessment procedures, any products declared through the ECO Platform will be comparable with other materials in the same category [27].

Therefore, the platform that aims to facilitate and coordinate the agreement between different EPD program operators should be encouraged and followed, and the EPD program operators around the world should consider working together to create a common EPD scheme.

Assumptions and Limitations

Based on the EN15804 standard, certain assumptions made during the LCA calculation are acceptable for specific stages to ensure the system boundary. There is no emission data for the drying process of EPD-IBU softwood, so the results from publication was cited. The gas used for the EPD-IBU softwood transport by forklift is estimated based on the GaBi database. The thermal energy and transport fuels consumed during the lifespan was assumed with the national average. However, these assumptions are made following the requirements of EN15804 standard.

There are also limitations for the continent comparison as the political, environmental and social

differences among different continents. For example, the EPD-IBU developed in Germany is specific to one product. The condition is linked to the specific situation happening with that product. However, the EPD-AWC and EPD-Australia are mostly represents the general performance of soft lumber industry in that country. Therefore, the data acquisition is more generic. These limits show that the harmonization is necessary in the same industry. On the other hand, these limits also present the development laps between different economics, and provide guides to the countries that are in the early stages of EPD development.

5. Conclusions and outlook

The general information and ISO framework for Environmental Product Declaration was studied and the international trend of EPD in different continents was discussed in this study. The EPD developments in construction products and building rating systems were also summarized in this study. The theory of EPD for building products and the related product category rules were also reviewed.

A comparative analysis was conducted for softwood EPDs from Europe, North America and Australia. The general information of the three EPDs was collected from the EPD publications, and the PCR reference standards and the declared units of the EPDs Investigated was analyzed. The system boundaries of the LCA studies for the three EPDs were fully investigated to ensure the input consistency of three EPDs, including the declared life cycle stages, the cut-off rules and assumptions. It was concluded from the LCA results that it is not feasible to compare EPD-AWC with the other EPDs due to the difference of the reference standard. EPD-IBU has a better performance than EPD-Australia in terms of environmental impacts and resource use, and the reason for that could be better analyzed if the LCA results for the product stage (A1-A3) could be presently separately.

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Green Building Construction Practices: Review of Environmental Management from the Contractor Perspective in the Canadian Industry

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Abstract:

Green building is a practice applied to the whole life cycle of a building, which means its environmental performance is not only defined by design, but also by the management processes in the construction, operation, and maintenance of a building. Over the past 10 years, research in green buildings has been increasing, mostly focusing on the design and energy efficiency. Contractors now represent a critical role in sustainability, but they have received less support and attention than the design community. This paper focuses on three main areas: practices on site, project management, and organizational support. While contractors in Canada are focusing on the implementation of green practices mainly established by LEED; a main problem is that the concept of "green" remains unclear and ambiguous in on-site practices. This research started with the identification of green building construction practices available to contractors by reviewing and comparing green building standards and literature review. Next, this research considered the management perspective by conducting semi-structured interviews in four construction organizations in order to document how LEED is integrated into project management and what issues companies are facing in the implementation of green construction practices. In addition, this research identified best practices in how these companies are supporting the reduction of environmental impacts during the construction phase. Overall, this paper highlights the different green construction practices that Canadian contractors can apply to advance their environmental sustainability, along with four case studies to document LEED construction management and an overview of the organizational tools used by companies for their environmental management.

Keywords:

sustainable construction management, sustainable practices, LEED, environmental management, contractor role.

1. Introduction

Literature such as journal papers, conference papers, reports, whitepapers, and books are replete with definitions, frameworks, and models to define and implement sustainability. Most of them start addressing sustainability from one of the most popular definitions for sustainable development mentioned in 1987 by the U.N World Commission on Environment and Development (WCED) in the Brundtland Report. According to the definition established, sustainable development refers to "development that meets the needs of the present without compromising the ability of future generations to meet their own needs". (WCED, 1987).

Sustainability is also generally described in terms of the triple bottom line. The triple bottom line goal was first established by John Elkington in his 1998 book, "Cannibals with Forks: the Triple Bottom Line of 21st Century Business" (USGBC, 2014), incorporating social, environment and economic perspective.

The definition of sustainable development and the triple bottom line seems to be applicable to every field from global development policies to the building industry. The building industry has a significant effect on the environment and human health as they consume more than one-half of the world's physical resources and account for 30% to 40% of the world's energy use.

(CSC, 2011). In this context, sustainability means creating places environmentally responsible, healthful and profitable (USGBC, 2014) and in order to achieve this, the building industry has been shifting the traditional practices to green practices.

Green building has been defined by many organizations. The US EPA defines it as the "practice of creating structures and using processes that are environmentally responsible and resource-efficient throughout a building's life-cycle from siting to design, construction, operation, maintenance, renovation and deconstruction" (US EPA, 2016). Essentially, green building is defined as the practice, method or even process of continual improvement (USGBC, 2014) applied to the whole life cycle of a building to increase efficiency and reduce its impacts, but not as the end product.

Green building growth in Canada has been promoted by building owners, institutional investors, corporate sustainability policies and building code/by-law requirements; but voluntary adoption has played a major role in the increase of green buildings. As of 2015, LEED buildings have eliminated 1,261,016 CO₂e tons of GHG emissions, diverted over 1.5 million tonnes of waste from landfill, and saved 12.8 billion liters of water per year in Canada (CAGBC, 2017).

Green building practices have evolved quickly, challenging the construction industry for a quick adaptation in their business practices and field operations (Tan et al., 2011). Contractors are participating and representing a crucial role in the success of green buildings as the implementation and documentation of some credits depend exclusively on them. (Rosenberg et al., 2003). For this reason, contractors are taking not just the responsibility in achieving sustainability requirements but also developing strategies to streamline the processes.

2. Research Objectives

This paper has three main objectives:

1. To identify the green building practices established in current green building standards that particularly impact the construction phase.
2. To document the integration of LEED construction practices in the project management areas established by the Project Management Institute.
3. To document the organizational approach from contractors for the implementation of green building construction practices.

To achieve the first objective, literature review and a comparison of five green building rating systems was conducted in order to identify green construction practices that can be implemented by contractors.

For the second and third objective, semi-structured interviews to four construction organizations were conducted. The main focus was on LEED management in green buildings, mostly considering pre-construction and construction phases, which fall under the project management team. Information about organizational support and tools for the management of green building site practices was also gathered through the interviews.

3. Environmental Management Framework

This research follows a framework method for the management of qualitative data. The framework used is shown in Fig 1.



Fig 1: Environmental Management Framework

The reason to use this framework is that each layer is fundamental to achieve the best outcome of environmental sustainability in projects. The technical aspects will define environmental practices to be

managed in the construction phase. However, the nontechnical aspect is equally important for successful implementation of green building. Management is believed to be the factor that most often determines the success or failure of a project (Imada 2002), (ISO, 2013), so this was included in the next two layers. Project management is "the application of the application of knowledge, skills, tools, and techniques to project activities to meet the project requirements" (PMI, 2013). A study suggested that project management factors such as human-resources oriented factors, technical and innovation-oriented factors, support from designers and senior management, project manager's competence, and coordination of designers and contractors are essential for the success of green building projects (Yuan Li et al., 2011).

The third layer arises because the construction industry is a project-based organization, creating "temporary systems" for carrying out their work. Project management activities should be aligned with top-level business direction and organizational strategy (PMI, 2013). Organizational strategy also relates to how environmental performance can be managed and controlled, including standards, organization policy and implementation systems (Poser et al., 2012). According to ISO 14031, management performance and indicators related to policies, people, planning, activities, practices, documentation, and procedures at all levels of the organization, including actions related to the environmental aspects will directly affect the performance in the organization's operations, influencing the environmental performance.

4. Green Construction Practices

LEED is a performance-based rating system that provides a framework for design, construction, and operation of buildings. LEED 2009, which is the version used on the case studies evaluates performance in seven key areas (Yellamraju, 2010) (CAGBC, 2010):

- Sustainable Sites: selection, design, and management of project sites.
- Water Efficiency: water reduction strategies.
- Energy and Atmosphere: energy efficiency of buildings and energy consumption.
- Materials and Resources: waste reduction and selection of sustainable materials.
- Indoor Environmental Quality: the improvement of the overall indoor air quality of buildings.
- Innovation in Design: innovative strategies not addressed by the other credit areas or exemplary performance, which means going beyond the normal requirements for LEED credits.
- Regional Priority: credits that have been identified to be important priorities for a particular region.

In addition to the achievable credits, there are certain prerequisites under each category that the project must meet. The number of points will determine the level of

certification. The levels that can be achieved are as follows:

- Certified: 40-49 points
- Silver: 50-59 points
- Gold: 60-79 points
- Platinum: 80 points and above

At present, sustainability in the construction industry often means applying LEED. LEED Canada NC-1.0 was introduced in 2004 and, since then, the number of certified building has grown rapidly from 31 certified buildings in 2005 to 2,576 buildings in 2015 (CAGBC, 2016). The Government of Canada established that LEED Canada has transformed the way that built environments are designed, constructed and operated—not only buildings but also homes, neighborhoods, and communities (Government of Canada, 2015). LEED will continue to be used to promote sustainability as building operators and corporate executives considered it to be a key way to communicate sustainability to stakeholders and to support corporate sustainability efforts (Long, 2015).

In a recent life cycle assessment study made for a 4000 m² office building, the construction phase represented between approximately 3% to 9% of the life cycle impact of the building (Delem et al., 2013). However, while LEED is widely implemented, it offers more specific recommendations in the planning and design phases of projects (O'Connor et al., 2015). This is problematic, as the environmental performance of a building is not only defined by the design features of a building, but also by the management processes for the construction, operation, and maintenance of a building (ISO, 2010).

Certain approaches and aspects of green buildings—such as energy efficiency—are becoming more standardized, but there is still a lack of common understanding in terms of site management (CSC, 2011). Also, research has focused on design and energy efficiency, while only 4% of the research relates to on-site practices (as reported in a study of the state of knowledge of green buildings, evaluating 218 papers and published in the International Journal of Construction Engineering and Management) (Owens by-Conte & Yepes, 2012).

LEED 2009 practices that most impact the contractor are site disturbance, material tracking, waste management and indoor air quality. (Syal et al., 2011)(Mago, 2007) Table 1 was developed to show a complete list of environmental technical and management practices that contractor can implement during construction. Practices considered were taken from the green building rating systems LEED 2009, LEED v4, Green Globes, BREEAM, REAP and two journal papers (O'Connor et al., 2016) (Zou & Sungwoo, 2013).

Table 1: Environmental Building Construction Practices

Category	Subcategory
Site Disturbance	Soil erosion
	Waterway sedimentation
	Airbone dust generation
	Limit site disturbances
	Site vegetation protection and restoration
	Tree preservation plan
	Staging and Construction Plan
Materials	Materials Reuse
	Recycled Content
	Regional Materials
	Rapidly Renewable Materials
	Certified Wood
	EPD
	Sourcing of Raw Materials
Waste Management	Material Ingredients
	Construction Waste Management Plan
	Waste Monitoring
	Total waste final report
	Minimum values for % of Waste Diversion
	Minimum # of material streams diverted
	Source Reduction Strategies
Indoor Air Quality	Adhesives and Sealants
	Paints and Coating
	Flooring Systems
	Wood Products
	Insulation
	Furniture
	IAQ Plan
	HVAC Protection
	Pathway interruption
	Housekeeping
	Scheduling
	Moisture damage to materials
	Policy for non-smoking
	Air-handlers filtration media
Equipment Related Practices	Flush-out
	IAQ testing report
	CxA authority
	Commissioning systems
	Commissioning final report
	Equipment energy efficiency
	Selection and replacement of equipment
	Reduction in idling of equipment
	Truck management plan
	Wheel wash /Tire-cleaning
Construction Site	Clean Diesel Practices
	Inspection and maintenance of equipment
	Energy Use Reduction
	Energy Monitoring
	Water Use Reduction
	Water Monitoring

	Monitor Transport Data Materials
	Monitor Transport Data Waste
	Assessment under local legislation
	Noise Management Plan
	Noise - Mitigation measures
	On-site monitoring measures
	Assessment under local legislation
	Equipment selection
	On-site reduction measures
	On-site monitoring measures
	Light Pollution
	Sustainable Temporary Facilities
Management Related Practices	Green Building Professional
	Green Building Professional Specific to Construction
	Environmental Management Tools
	Environmental Policy
	Regulatory Compliance and Training
	Environmental Risk Assessment
	Environmental Risk Management Strategies
	Environmental Management Roles, Responsibilities and Reporting Structure
	Site and Work Instructions for site personnel
	Environmental Inspection Checklists
	Records of Compliance
	Train Workers for Emergency Response

The most frequently implemented green site practices by Canadian contractors are reuse of buildings materials, recycling, and site protection, which are already established by LEED. (CSC, 2011) On-site energy conservation was the next most prevalent, which can increase profit margins, improve resource efficiency, and reduce environmental impacts (Gottsche et al., 2016). Relevant practices that can be applied on-site, not covered by LEED, concluded from Table 1 are:

- Monitoring Energy Consumption: related to equipment and site.
- Monitoring Water Consumption: related to equipment and site.
- Monitoring of Transportation Data: not only from materials, but also from the evacuation of soils and waste, which means monitoring the truck from the construction gate to waste disposal.
- Equipment Related Practices: reduction of idle times, clean diesel practices, selection and maintenance of equipment, tire-cleaning and a truck management.
- Environmental Management System: includes environmental policy, environmental inspection checklists, records of compliance, management strategies, reporting structure, and more.

5. Case Study Information

Semi-structured interviews were conducted in four construction organizations. The information about the companies is shown in Table 2. The person interviewed was either project manager or project coordinator who had knowledge of environmental practices implemented on site.

Table 2: Case Study Information

1	Company: •General contractor •International company with a Canadian subsidiary •Operate in all provinces in Canada •Offices in Toronto, Ontario and BC Project: •Design-build project •School project under LEED 2009 •LEED Gold •Upgrade project •Located BC
2	Company: •General contractor & construction manager •Operates in BC •Focus is on multi-unit residential, commercial, light industrial, recreational, institutional and municipal construction projects •Services range from development management, general contracting, construction management, and other project delivery methods. Project: •No specific project
3	Company: •International company •Operates in all provinces in Canada •Focus on large commercial, institutional and civil construction projects Project: •Construction Management •New construction and renovation project under LEED 2009 •LEED Silver •Located in BC
4	Company: •Services range from preconstruction, construction, virtual construction and work with several project delivery methods •Operate in BC and Alberta •Focus on commercial, residential and institutional buildings Project: •Design –bid-build •Residential building with community centre, park and plaza •LEED 2009 Gold •Located in BC

6. Results and discussions

a. Project Management Perspective

Management practices must be modified in order to incorporate sustainable practices into design and construction processes (Syal et al., 2011). There are a number of project management frameworks in existence for a variety of purposes. The ones chosen as foundations for this paper were based on the book "LEED-New Project Management" (Yellamraju, 2010) and the fifth edition of the Project Management Body of Knowledge (PMI, 2013).

The Guide to the Project Management Body of Knowledge, known as the PMBOK Guide, was developed by the Project Management Institute to provide guidelines for managing individual projects, define project management related concepts, and describe project life cycle and related processes (PMI, 2013). The PMBOK Guide describes 47 project management processes within 5 project management process groups and 10 knowledge areas. This paper used the knowledge areas, which are mainly defined as "set of concepts, terms, and activities that make up a professional field or area of specialization" to categorize the information obtained in the case studies. The knowledge areas are integration, scope, time, cost, quality, human resources, communications, risk, procurement, and stakeholder management.

The companies were asked how LEED is integrated in project management. Three of the companies mentioned that scope and cost management were the most impacted by LEED. The results obtained are summarized in Table 3.

Table 3: LEED integration in Project Management

Integration	•More Diligency with Change Orders •More Design Reviews
Scope	•Overall Project Administration •LEED Plans •LEED Calculations •LEED Implementation Documentation •Response for GBCI after months
Time	•Meetings integration with master schedule •Inspections Integration with master schedule •Document submission deadlines •Follow up time for certification •Scheduling of activities
Cost	•Total Project Cost •Cost Estimations Presentation •Administrative costs: Paperwork + LEED Coordinator
Quality	•Additional inspections on site •Quality of trades •LEED review progress

Human Resources	•Additional training for Subcontractors •Additional team member •Additional team responsibilities •Green knowledge/ experience
Communication	•Client reporting •LEED Consultant •Weekly /monthly meetings •Pre-kick off meeting
Risk	•Penalty for compliance •Risk considerations for delays for doc. •Risk considerations for delays for measures •Emergency response strategies
Procurement	•Specs in Contracts and Agreements •Availability for materials
Stakeholder	•More client engagement to the project

Participants were also asked to provide common issues concerning green construction practices implementation, including: material tracking, waste management, site disturbance and indoor air quality. The severity and impact of each issue were also asked about, and the results were classified and presented in Table 4. The impact and severity considered are shown in Figure 2, where HS stands for high severity, HO for high occurrence, LS for low occurrence and LO for low severity. The table also presents several abbreviations to better display the information: W stands for waste management, SD for site disturbance, IAQ for indoor air quality and M for materials. The number displayed in brackets represents the number of the corresponding case study that specifically emphasized that issue.

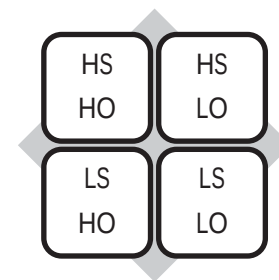


Figure 2: Impact and Severity Matrix

Table 4: Practices Issues in Project Management Areas

Integration	M: Design Change [HS,HO][2]
Scope	SD: Site specific details not considered early in the process [HS,LO] W: Wrong estimates of waste [HS,LO][1] W: Poor diversion strategies [HS,LO][1]
Time	W: Poor construction scheduling [LS,HO] IAQ: Occupancy required before flush-out [LS,HO] W: Site Layout since the beginning of project [HS,LO] [3]
Quality	SD: LEED Consultant experience about constructability issues [LS,HO] W: Collaboration of Site Workers [LS,HO][2] W: Knowledge of Measures [HS,LO] IAQ: Trades knowledge of measures [LS,LO]
Human Resources	SD: Poor record keeping procedures [HS,LO] W: Poor record keeping procedures [HO,LO][2]
Risk	M: Delays for incomplete documentation [HS,LO] SD: Delays for not measures in place [HS,LO]
Procurement	M: Wrong spec. For materials in contract doc. [HS,LO] W: Wrong documentation from subs [HO,LO][2,1]

b. Organizational Perspective

One of the main reasons for which contractors are increasing their level of green activity is to improve their branding/public relations (CAGBC, 2014); therefore, they will try to incorporate green construction strategies to differentiate their businesses from others. These strategies are supporting the current green building standards.

McGraw-Hill conducted a study demonstrating that only 9% of construction companies actually transformed sustainability into their organization and daily practices (McGraw Hill Construction, 2012). Therefore, it is important to develop organizational transformation strategies that allow companies to successfully adopt and implement sustainability (Kang Hee, Ahn, Jeon, & Suh, 2014).

This research is intended to identify best practices relating to the organization perspective. Best practice research relies on the idea of communicating and transferring practices that seem to work well somewhere else. Best practice research—also referred to as "good practice" and "smart practice"—has been described as being practical and useful (Vesely, 2011).

Participants were asked to describe how their companies support green building construction practices implementation and the results are summarized in Table 5.

Table 5: Organization Tools for Green Building Practices Implementation

Company	Organizational Support
1	Guidance for On-Site Practices • Specific sustainability model • In-house <i>Environmental Label</i>: Based on ISO + Environmental Stds (BREEAM + LEED) from Parent Organization • CANADA: LEED Protocols • Integrated Health and Safety Policy Measurement Framework • Environmental Inspection Report (Performance Indicators) • Sustainability Reporting Available Initiatives • Promote solution for reducing carbon footprint • LCA for promotion of new construction methods and low carbon materials • Calculate carbon footprint
2	Guidance for On-Site Practices • Operations Manual /Guidelines • LEED Protocols Measurement Framework • Inspection report (Performance Indicators related to LEED) • No Sustainability Reporting Available Initiatives • Site-specific green building initiatives • In house consultants (commissioning) • Provide in house administrative requirements for certifications
3	Guidance for On-Site Practices • Specific sustainability model • EMS: based on ISO • Integrated Health + Safety Policy • LEED Protocols Measurement Framework • Environmental Inspection Report (Performance Indicators) • No Sustainability Reporting Available Initiatives • Office space guidelines • Company evaluation /reporting

7. Conclusions and outlook

Canada's green building industry has grown quickly, but more training and support is needed to help the

construction industry to understand, design and build buildings that achieve high environmental, economic and social aspirations (CAGBC, 2016). As a general contribution, this research provides a review of green building construction practices and environmental management in the Canadian industry from the contractor's perspective.

This research can be used as a guideline for contractors that are trying to improve or incorporate more green construction practices in their operations. Section 4 details a number of practices beyond LEED that will help reduce the environmental impact of the construction activities. These practices were determined by reviewing different green building standards, complemented with the review of several journal papers.

In addition, this paper reviewed the project management perspective by conducting semi-structured interviews in four construction organizations. This contribution is to show how LEED is integrated into construction project management and by identify the issues related to material tracking, waste management, indoor air quality and site disturbance facing Canadian contractors.

Finally, this research determined several best practices in organization tools that can support the implementation and management of green construction practices.

The three main conclusion from this paper are:

1. Contractors are looking for guidance and resources for conducting sustainable construction activities to improve their sustainability performance. The practices from LEED 2009 that most impact the contractor are:

- Site disturbance
- Material Tracking
- Waste Management
- Indoor Air Quality

However, there are other construction green practices that contractors can apply in their projects. Contractors can support environmental sustainability by monitoring energy and water consumption on site, in addition to just reduction techniques. Additional practices can be monitoring of transportation data, equipment related practices and management techniques such as an EMS (Environmental Management System).

2. LEED is highly integrated into project management practices and—even though it is not considered as an "impact"—the companies still identified that LEED mainly affects the PM areas of scope and cost management. Other issues related to green practices are related to materials coordination, waste management, indoor air quality and site disturbance. The most serious issue was related to human resources management. A lack of collaboration and knowledge of subcontractors and the workforce are reported to be the main cause of issues in material coordination, indoor air quality measures, site

disturbance inspections and waste management procedures. General training on green buildings for subcontractors and field supervisors is considered as the most effective strategies to mitigate these problems.

3. The best practices identified were as follows:

1. Follow LEED guidelines on projects, even if the formal certification process is not pursued.
2. Go above the minimum standards by advancing the level of performance called for in LEED practices.
3. Use an EMS to assess environmental performance and to manage environmental policy.
4. Create an environmental label or designation specific to the worksite based on a combination of management and technical aspects from LEED, BREEAM, ISO 14001, and others.

Future Research suggested is:

1.Green Construction Practices: this research focused on investigating environmental practices established in green building standards and research, but it can be extended by including social and economic practices that specifically impact the construction phase to provide broader guidance on sustainability management from a contractor's perspective.

2. Project Perspective: this research was focused on LEED 2009 case studies. The same approach can be taken for projects under different certification systems such as LEED v4 or Living Building Challenge.

3. Organization Perspective: this research focused on an overview of the organizational approach to environmental management. However, it could be extended to a more detailed case study evaluating the details of organizational structure, sustainability indicators and reporting systems.

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Mitigating risks and overcoming barriers in Canadian renewable energy projects: A partnering approach

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Abstract:

Interest in renewable energy systems and net-zero energy communities has grown in the recent times due to environmental and economic pressures. However, a multitude of barriers stand in the way of increased renewable penetration. The heavy financial burdens and the requirements for specialised technologies and infrastructure lead to real and perceived risks regarding renewable energy systems. These challenges discourage stakeholders from adopting renewables to replace the conventional energy sources, especially at the community level. In order to promote and enhance the viability of renewable energy projects, it is necessary to manage the risks and incentivise the stakeholders. Energy planning involves stakeholders at various levels, ranging from federal and regional government, investors and developers, to the general public. Renewable portfolio selection for minimised risk and maximised benefits needs to be done at the pre-project planning stage in order to fulfill the expectations of all these stakeholders. Contracting strategies for resource procurement, power purchase agreements, and technology partnerships can be used to manage the financial and operational risks related to renewable investments. Further, suitable investment mechanisms need to be provided to surmount the funding barriers and agency problems arising in renewable energy projects. Finally, policies and regulatory instruments from the governing bodies can incentivise and remove the obstacles to renewable energy systems. This paper discusses how risk mitigation and incentivising approaches can be combined in a comprehensive partnering roadmap, which synchronises stakeholder efforts at all levels to support increased renewable penetration. The findings will benefit community level planners and developers, as well as policy makers at regional and federal levels in their energy-related decision making.

Keywords:

Energy planning, renewable energy risk mitigation, energy project partnering, decision making

1. Introduction

While renewable energy (RE) planning is a highly discussed topic with the current drive towards climate change mitigation [1], there is yet a long way ahead for large-scale RE penetration in Canada. By 2013, 22% of the global power generation was from renewable sources, and this is projected to increase up to at least 26% by 2020 [2]. In the same year, 75% of Canada's primary energy production (heat and electricity) was from fossil fuel based sources, with hydro and other RE sources supplying only 11% [3]. Thus, a significant potential exists within the country to replace conventional energy sources with RE [4]. Developing decentralised energy systems at community level energy systems can help in adapting the planning and design to better suit the local conditions and requirements. [5]. In this type of RE projects, the local stakeholders are actively engaged in the decision making process [5]. Hybrid distributed energy systems are now being promoted as the future in energy generation, as community energy needs continue to grow and diversify [6]. Canada has committed to the United Nations climate change conference goals in Paris (COP21). By 2030, the Government of Canada aims to cut down greenhouse gas (GHG) emissions by 30% of the 2005 levels [7][8]. Increased RE penetration is vital in achieving the above goal, particularly as 80% of the Canadian GHG emissions are caused by the use of energy in

some form [9]. Energy use also creates economic burdens, which impact individuals, communities, and countries [10]. RE project can have other positive impacts on communities, such as contribution to local economic development, and job creation [11][12][13]. Improving the energy security, energy independence, and access to energy, while reducing energy poverty are key goals in developing community level RE systems [11][14].

Decision making in developing RE powered community energy systems is a complex exercise due to the presence of a wide array of conflicting objectives and constraints. As many different stakeholder parties are involved in the process, varying requirements and priorities have to be accommodated [15]. There are many challenges associated with practical RE project delivery. Energy planning involves stakeholders at various levels, ranging from federal and regional government, investors and developers, to the general public. Perception of risks associated with RE projects often hinder increased RE penetration [16]. In order to promote and enhance the viability of renewable energy projects, it is necessary to do extensive planning, manage the risks, and incentivise the stakeholders [17][14]. Taking a multi-stakeholder and multi-period project management perspective is therefore critical to ensure the success of RE projects. The objective of this paper is to discuss how risk mitigation and incentivising approaches can be

combined in a comprehensive roadmap for managing challenges and effective implementation in community level RE projects, which synchronises stakeholder efforts at all levels to support increased renewable penetration. The discussion will be aimed at the development of community-level energy systems, which can replace the conventional centralised energy supply in the quest to develop net-zero communities [18]. While other initiatives such as energy conservation, alternative transportation, energy sharing, and waste heat recovery are important in developing community energy plans, the scope of the material discussed in the present study is limited to renewable energy integration at community level. The findings will benefit community level planners and developers, as well as policy makers at regional and federal levels in their energy-related decision making.

2. Renewable energy project management

Projects can be generalised into five different stages in their life cycle; initiation, planning, execution, control, and termination [19]. In a RE project, various stakeholders are involved in each of these phases, including the government and other authorities, community developers and planners, consultants and contractors, as well as the local community. The motivation for RE projects is established considering the baseline requirements, economics, policy issues and incentives, technology, and the consensus among stakeholders [20]. At the initiation of an energy project, the portfolio selection needs to be conducted based on the available energy resources. The selection criteria may be in the form of availability, supply reliability, maturity of the technology, and location [21]. Based on the expected costs and energy generation potential, the business case needs to be proven for the proposed energy system [20]. The economic merits of the renewable energy investment need to be considered within the project funding boundaries. Further, a technical assessment is necessary on the engineering and operational risks of the selected technologies [22]. The planning stage of a RE project involves budgeting and financing, risk management, labour and resource procurement strategies, and assessing the regulatory compliance [16]. In operationalising RE projects, obtaining the necessary technical expertise, allocating operational responsibilities, and generating commercial returns on the produced energy are key issues [23][24]. In addition, procurement of the necessary labour and resources for the RE generation facilities needs to be considered. During the life cycle of RE facilities, routine maintenance, rehabilitation, and any required upgrades need to be carried out. At the end of life of the facilities, it is necessary to make decisions about the disposal and the continuity of the RE system [25]. The responsibilities of these activities can be allocated to various stakeholders based on the operationalising mechanism and ownership preference structure. Based on the above, RE project implementation at community or municipal

level can be summarised through the stages of the project life cycle as depicted in Figure 1. Identifying these factors is the first step in developing a comprehensive roadmap for successful RE project implementation.

At each of the above mentioned project life cycle stages, careful planning is necessary to mitigate the issues and barriers. To guide the communities towards the best outcomes in shifting to RE, it is necessary to formulate best practices and define an integrated framework on implementation. However, a project management perspective and a combined approach to synchronise stakeholder efforts is lacking in the previously published literature.

3. Barriers, risks, and challenges

Risks and barriers associated with RE projects can be manifold. These risks, barriers, and other challenges have a detrimental effect in the propagation of commercialised RE integration at community level. A study conducted by Angelis-Dimakos et al. in 2011 indicates that there are three levels to renewable energy potential. These are the theoretical resource availability, the technical potential influenced by technology efficiencies and accessibility, and the economic potential [26]. At a very basic level, resource availability as well as geographic and other locational conditions (e.g. climatic conditions, weather fluctuations) act as constraints to RE penetration [26]. There should be sufficient availability of the resource in close proximity to the site location of the community, which can also be sourced, transported and converted to energy with minimal economic and environmental burdens [27][28]. Resource availability, energy demand, generation capacity and efficiency are all subject to uncertainties [29]. Moreover, non-dispatchable energy sources such as solar and wind are intermittent in nature, and the power generation from these resources fluctuates with environmental conditions [30]. This unreliability in resource availability needs to be taken into account in decision making for RE planning [29].

Once the theoretical and technical potential of a RE system has been ascertained, it is necessary to establish the economic and social viability of the proposed energy project. Uncertainties contribute to making RE project planning even more complex. Maintaining the balance between the energy demand and supply is important, and this leads to uncertainty in forecasting, defining the energy mix, and predicting economic and environmental burdens [16]. Social risks such as land availability, political factors as well as legal and regulatory issues are difficult to quantify, and can only be assessed in qualitative form in most cases [16]. Energy planning for communities is also subject to the influence of macro-economic factors, which undergo continuous variations. Risk management plays an integral role in making an RE project viable [31]. Data uncertainty is another critical

issue faced in RE planning. The information obtained on environmental and socio-economic factors, locational parameters such as geography and climate,

as well as demand and price forecasts are usually vague, incomplete or imprecise [29].

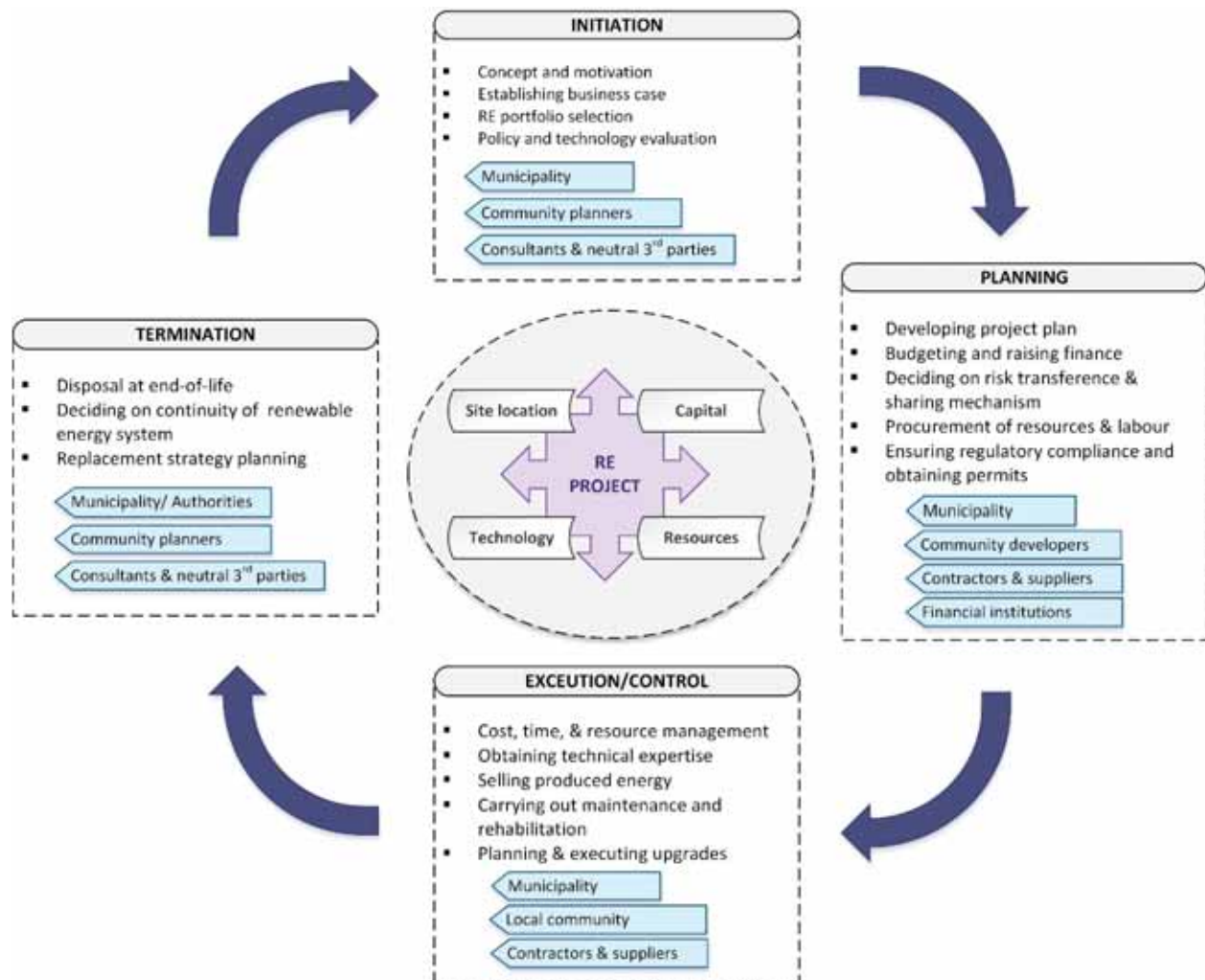


Fig 1: Picture of an insulation specimen, Text picture text picture

The potential variations in economic, environmental, social, legislative and technical factors as well as resource availability with time needs to be taken into account in dynamic energy planning [29]. To increase the acceptance of RE systems among community-level decision makers and other stakeholders and increase RE penetration, it is necessary to provide some means of quantifying the associated risks and estimate the viability of these systems at the planning stage [16]. Figure 2 summarises the risks and contributing variables factors affecting energy system implementation at community level.

Risks have implications on the viability and future stability of energy systems. Risk assessment can be used to indicate whether the system is financially and economically feasible, and whether it can meet the local energy demand as anticipated [17]. It can also provide an estimate of the suitability of installing such a system with respect to environment, human health, or other socio-cultural aspects. In addition to risks, other challenges and barriers hinder the promotion of RE penetration, including funding issues, lack of social acceptance, policy and regulatory barriers, and difficulties in operationalising. Some key challenges and opportunities in planning and delivery of RE projects are summarised in Table 1. Different deployment mechanisms can be used in planning and operationalising RE projects to mitigate and solve the below mentioned challenges.

The above issues lead to direct and indirect impacts on the stakeholders involved. An example of an indirect impact is how the housing prices of a newly built community with RE integration can increase due to the additional cost of RE infrastructure [24].

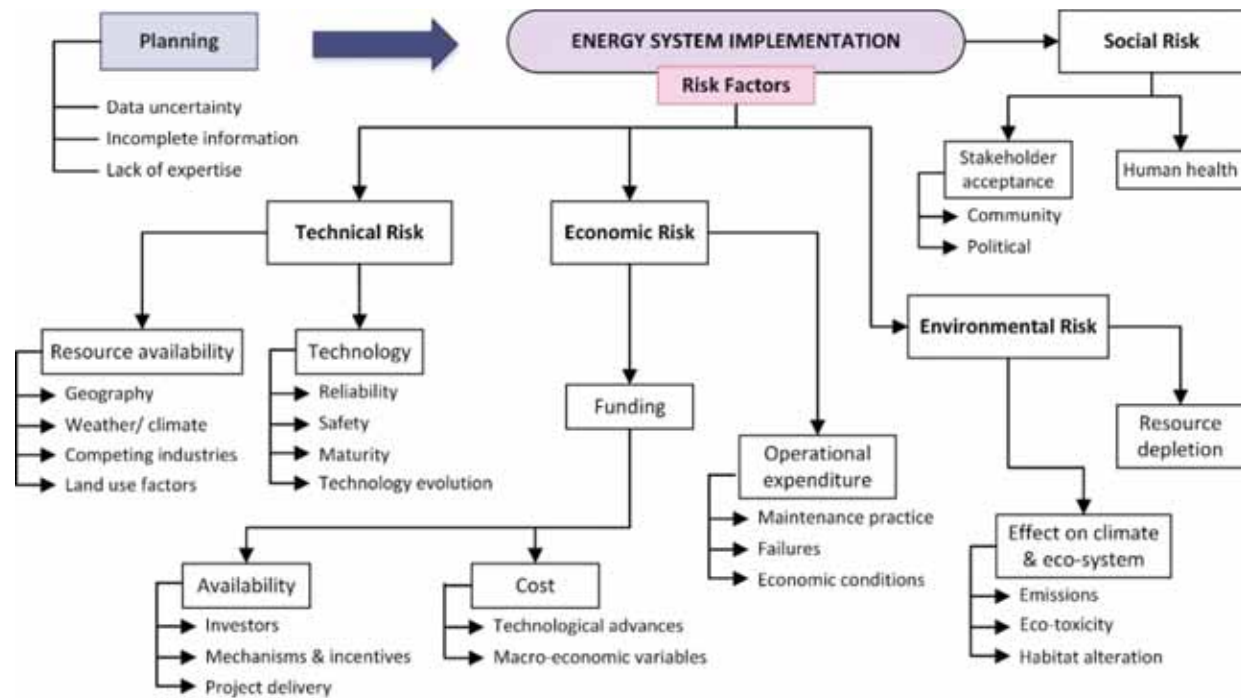


Fig 2: Risks in energy system implementation

Table 1: Classifying issues and solutions in RE project planning

Issue	Challenges / Barriers	Opportunities / Solutions
Geographic location	- Availability and feasibility of RES vary by location [17] - Lack of access to grid connectivity, infrastructure, technology or knowledge in remote regions [32]	- Selection of locally suitable RE technologies - Possibility of developing self-sustained standalone net-zero energy communities [33]
Funding	- Project finance gap – The development of optimised RE systems needs to varied out under the constraint of limited funding allocations [16]. - Split incentives in investment motivation (agency problems)– The party who incurs the additional costs of RE integration may not derive any direct benefit [32]	- Cost sharing agreements with local governments/ other entities [34] - Strategic alliances and agreements with financial institutions [16] - Government policies and funding mechanisms (i.e. tax breaks, grants, low interest loans) [35] - Carbon emission reduction credits [35]
Risks and uncertainties in planning	- Economic and technical risk [17] – Changes in external environment and technological evolution, and lack of precedents make planning difficult - Vague, incomplete and imprecise information leading to uncertainty in planning [29]	- Site analysis for risks & identifying acceptance levels [36]; - System dynamics modelling and risk analysis for long-term energy planning [17] - Decision support tools for planners [37]
Social acceptance	- Socio-cultural barriers, and lack of incentive for acceptance of new RE technologies and behavioural changes [32] - Adverse perception of risk [32]	- Multi-stakeholder view based RE planning - Stakeholder consultation during planning phase of energy systems [32] - Systematic risk management approach [16]
Operational	- Allocating responsibility for operations and maintenance of RE facilities - Challenges in obtaining the necessary technical expertise for the communities [5] - Challenges in selling the generated power and making a business case [38][39]	- Developing community level management plans [5] - Providing guidelines and decision support for energy systems management [40] - Agreements with third party contractors and suppliers, and power purchase agreements with utility providers [16]
Policy and regulations	- Regulatory barriers to technology penetration, and grid integration and transmission issues [41] - Lack of coordination between stakeholder groups, especially at administrative levels [32] - Absence of consistent policies and guidelines in RE project planning and management [32]	- Policy incentives and regulatory changes for promoting RE [32] - Streamlined process for RE planning to combine all levels of decision making - Infrastructure and technology development to accommodate RE integration [11]

The challenges and opportunities affect different stakeholder groups to varying extents, and thus the importance of a particular challenge or an opportunity can be change by stakeholder type. The matrix approach given below is proposed to quantify the challenges and opportunities applicable to different stakeholder groups. A sample of ten examples has been selected under both challenges and opportunities to demonstrate the proposed approach. The key stakeholder groups have been identified as follows; government authorities such as municipalities (S1), project developers (S1), utility providers (S3), academia and researchers (S4), community/ residents (S5), energy service companies and consultants (S6). The importance of each challenge and opportunity to

the stakeholders has been allocated a rating on a Likert scale on five levels as “very low”, “low”, “medium”, “high”, and “very high”. The “very high” rating is measured as 5 on the scale, and “very low” is measured as 1. Linguistic ratings have been commonly used to denote qualitative criteria [42]. While stakeholder groups such as municipalities, local community, and community developers are the ones who mainly face the challenges in RE project development, other stakeholder groups such as energy service companies, consultants, academia, and utilities can bring forth solutions and exploit them. By joining forces, these two types of stakeholders can complement each other, leading to mutual benefits.

Table 2: Selected opportunities and challenges

Challenges		Opportunities	
C1	Limited availability of capital	O1	Cost sharing agreements and strategic alliances
C2	Split incentives leading to agency problems	O2	Subsidies and funding mechanisms
C3	Limitations in RES availability & technical risk	O3	Emissions reduction (carbon) credits
C4	Lack of access to knowledge and expertise	O4	Feasibility assessment, performance assessment, & benchmarking
C5	Difficulty in making a business case for RE	O5	Developing planning tools and guidelines through research & development
C6	Uncertainty in planning due to vague, incomplete, and imprecise information	O6	Sharing data among communities with similar energy needs and vision
C7	Regulatory, policy, and institutional barriers	O7	Developing standalone net-zero communities
C8	Managing operational & maintenance responsibilities	O8	Policy incentives and regulatory changes
C9	Utilising and selling the generated power	O9	Outsourcing project delivery through contracts with energy service companies
C10	Lack of access to grid connectivity and other infrastructure	O10	Agreements with 3 rd party contractors, utility providers, and suppliers

Stakeholders*	Challenges										Opportunities									
	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	O1	O2	O3	O4	O5	O6	O7	O8	O9	O10
S1	5	1	5	5	5	5	5	5	5	3	5	5	-	5	5	5	3	5	5	5
S2	5	5	3	5	5	5	5	-	-	5	5	5	5	5	5	4	3	5	5	5
S3	-	-	-	-	2	1	3	-	2	1	3	3	3	2	2	3	3	3	3	2
S4	-	-	-	-	-	1	-	-	-	-	-	-	-	5	5	3	3	-	-	-
S5	-	2	5	3	-	-	-	5	3	2	-	2	2	-	-	2	5	1	3	-
S6	-	2	-	-	-	3	4	-	2	2	5	2	5	5	5	4	2	4	5	5

*government authorities such as municipalities (S1), project developers (S1), utility providers (S3), academia and researchers (S4), community/ residents (S5), energy service companies and consultants (S6).

Fig 3: Matrix of challenges and opportunities for stakeholder groups

To further quantify the opportunities and challenges for each stakeholder, and to measure the relative impact of a challenge or an opportunity, the scores assigned to opportunities/challenges can be summed up. The relative importance of a challenge or an opportunity can be denoted by assigning it with a relative weight, which is an approach used in previous studies [43]. Summarising the information on opportunities and challenges in this manner can facilitate multi-stakeholder engagement in a more effective manner, and to decide which issues to focus

on based on their relative impact and importance. Stakeholder surveying is one method which can be used to obtain information on the relative importance of different issue and their impacts [44]. Following this step, various project deployment mechanisms can be used to mitigate challenges and exploit opportunities, as described in the following section.

4. Mechanisms for mitigating RE project issues

Mitigation mechanisms can be classified according to the type of issue they are expected to address. The opportunities and solutions mentioned in the previous section can be exploited using various project deployment strategies. At the initial concept stage of a RE project, the deployment strategy needs to be selected. A community which needs to move to RE based power may decide to go for centralised energy generation through micro-grids or local grid tied energy systems, or alternatively it may decide to push a user-level structure where distributed RE generation is incentivised for individual ordinary energy users (e.g. households, industries, businesses). A study by Koirala et al. (2016) lists the following models for

energy system integration; community micro-grids, virtual power plants where distributed energy resources at consumer level are aggregated and managed, energy hubs with multi-carrier optimisation, prosumer community groups where energy is exchanged among stakeholders with similar goals who produce and consumer energy, community operated energy systems, integrated community energy systems which combine distributed energy resources, flexible loads, storage, and different carriers [14]. Each model for RE system deployment comes with its own challenges, and requires careful assessment and planning prior to implementation. Table 3 summarises some of the requirements different stages or RE project life cycle, issues to overcome, and potential mitigation mechanisms.

Table 3: Mitigation mechanisms for RE project issues

Stage	Requirement	Issues to overcome	Mitigation mechanisms
<i>Initiation</i>	Concept and feasibility assessment - In order to determine which energy system model is most suitable for a community, to define the RE portfolio and minimise the risks, it is necessary to assess the performance and feasibility of the proposed system [45][46]	- Need to obtain expertise - No prior experience and knowledge base on RE project planning [47] - Data unavailability - Uncertainties in assessment and planning [29] - Lack of motivation and incentives to shift to RE	- Collaborative R&D with academia and other neutral third parties [48] - Contracting energy consultants and suppliers [49] - Developing an integrated data sharing platform to connect community RE efforts - Formulating decision support tools and best management practices - Implementing Renewable Portfolio Standards (RPS) or renewable obligations [16][50]
<i>Planning</i>	Funding mechanisms and stakeholder satisficing - Means of financing the project need to be established. In addition, planning should meet the stakeholder needs, and distribute the risks and benefits in an equitable manner among all stakeholders.	- Raising capital for the project [20] - Lack of investments - Assuming, transferring, and mitigating risks [16] - Bringing stakeholders to a consensus and goal congruence [20] - Getting necessary permits & regulatory compliance [51]	- Third party financing - leasing and power purchase agreements [52] - Grants, subsidies, and other fiscal incentives by government, and preferential loans by financial institutions for RE efforts [53] - Long term contracts to RE producers and tradable green certificates [54] - Creating consortiums with suppliers, EPCs ¹ , utility providers, and financial institutions for risk resiliency [16] - Hedging significant risks [16] - Use of bank guarantees or insurance [16] - Knowledge dissemination among stakeholders - Developing a common platform for stakeholders to engage [48]
<i>Execution & control</i>	Continuity of operations and value generation - The operational and maintenance responsibilities of the energy system needs to be allocated. The generated energy needs to be distributed and sold to generate economic value.	- Need for continued technical assistance in operations - Procuring resources and labour in a reliable manner - Carrying out maintenance activities & upgrades - Ensuring economic returns - Ensuring continuity of supply	- Turnkey projects and operational outsourcing to ESCOs ² through EPCs [49][55] - Agreements with suppliers and contractors [49] - Energy exchange with similar prosumers [14] - Feed-in-tariff schemes with energy generation by individual consumers [56] - Agreements with utility providers for buying (power purchase agreements) [20] - Renewable energy credit schemes [20]
<i>Termination</i>	Disposal and replacement of energy system - At the end of life of the system, the outdated facilities need to be disposed of, and system continuity needs to be planned.	- Post-project outcome assessment - Disposal with minimal environmental impacts [57] - Planning energy system continuity	- Technology evaluation - Collaborative research with academia and neutral third parties [48] - Benchmarking through knowledge sharing with similar RE systems and communities [58]

¹ Energy performance contracting

² Energy Service Companies

In addition to the above mentioned mitigation mechanisms, supportive policies and regulations from the governmental bodies directed at promoting RE project will be greatly beneficial in the overall promotion of RE [32].

The economic success of a RE project depends on planning, and it has been identified that a project should usually have at least 20-30% of margin above the general estimate of costs to cover for variations due to profit and uncertainty, it may not be economically successful [20]. While raising the necessary funding themselves through capital budgeting or equity can be difficult for communities or business entities, partnering with other entities through strategic alliances, consortiums, and contracts can make RE projects financially viable. Third party ownership financing structures have been used in the US solar sector in the form of leases and power purchase agreements (PPA) [52]. In a lease, a contract is made by the customer to pay the developer for using the RE system for a predetermined time period, instead of paying by the amount of power generated [52]. In contrast, the PPA model is used in renewable electricity projects for guaranteed power sales to large scale entities such as utility providers at a fixed rate [41]. Feed-in tariffs ensure that RE producers get government fixed prices for generated power, and guarantees the security for long-term RE investments, thus in turn motivating production [16]. Similarly, renewable credit schemes or renewable energy certificates (REC) are used to trade and share the benefits of RE implementation among various groups. RECs are market based financial instruments which are tradable energy commodities [59]. Similar to carbon credits, they can be used to claim RE use and carbon footprint reduction, and an entity which does not generate RE on its own can acquire credits from a producer. These schemes are supplemented and promoted at policy level by renewable portfolio standards (RPS) or renewable obligations, which requires and sets minimum quotas for RE generation.

Benchmarking is a common approach used in energy related endeavours (especially in the energy efficiency sector) to make sure whether the efforts are sufficiently successful, and can thus be adapted to RE project evaluation [58]. Lack of past performance data and experience is a key challenge in benchmarking RE projects and assessing their outcomes. This can be alleviated through knowledge sharing, and developing open-source integrated data sharing platforms can effectively transfer knowledge and technical experience [60]. This knowledge can also help in effectively planning the continuation of the energy system

Having a sound risk mitigation strategy is essential in achieving stakeholder acceptance to RE projects. Risk sharing and transferring consortiums developed among community developers, financial institutions, suppliers, energy service companies, and utility providers can help in transferring risk and limiting the risk incurred by one party, thereby aiding stakeholder congruence. In addition to this, government grants and subsidies as well as preferential loan schemes may be beneficial in alleviating the financial risks [51][53]. Financial institutions may be further encouraged to provide preferential loans to RE projects with the introduction of policy instruments such as RPS. Another major challenge to RE project implementation is the lack of access to grid and other infrastructure. Players such as large-scale established utility providers can help in mitigating such issues for emerging RE projects. In essence, with all the above mitigation strategies, it can be noted that solutions cannot be brought forth by the efforts of a single group, but can only be realised through the combined and coordinated efforts of multiple parties.

5. Roadmap for managing RE project challenges

As discussed in the previous sections, there are many mechanisms available to alleviate the problems associated with RE projects, and to exploit the opportunities. However, at present, they are being used in a disjointed manner to solve the challenges in RE deployment. Depending on the access to different financial, technical, or other risk mitigation mechanisms and the level of knowledge and experience available, RE project developers are using one or more of the above strategies to ensure the viability of their projects. One of the most critical tasks in the way forward for RE project management is developing an integrated and cohesive framework to synchronise these efforts and various stakeholder groups, and thereby to devise a strategy to streamline the RE project deployment at community level. In this manner, instead of selecting from a limited range of options for project deployment mechanisms and risk mitigation, communities are given more flexibility in customising project delivery to suit their conditions and needs. While outsourcing the energy system development and operations may be the best option for one community, developing consumer level RE generation facilities to operate as virtual energy hubs may be more beneficial for another. By opening up a variety of financing, risk mitigation, and operational options, a combined partnering framework makes a wider range of RE project scenarios viable for communities. By bringing all stakeholders to a common platform and obtaining their support to develop renewable energy consortiums at regional level, communities are strengthened in their clean energy efforts. The other stakeholders in the partnering framework such as energy service companies, financial institutions, and utility providers also benefit from this arrangement, by being allowed to reap the benefits of RE deployment. It ensures that none of the relevant stakeholders are left behind in the inevitable shift to a clean energy future.

Figure 4 illustrates the proposed integrated roadmap for value chain management in RE projects.

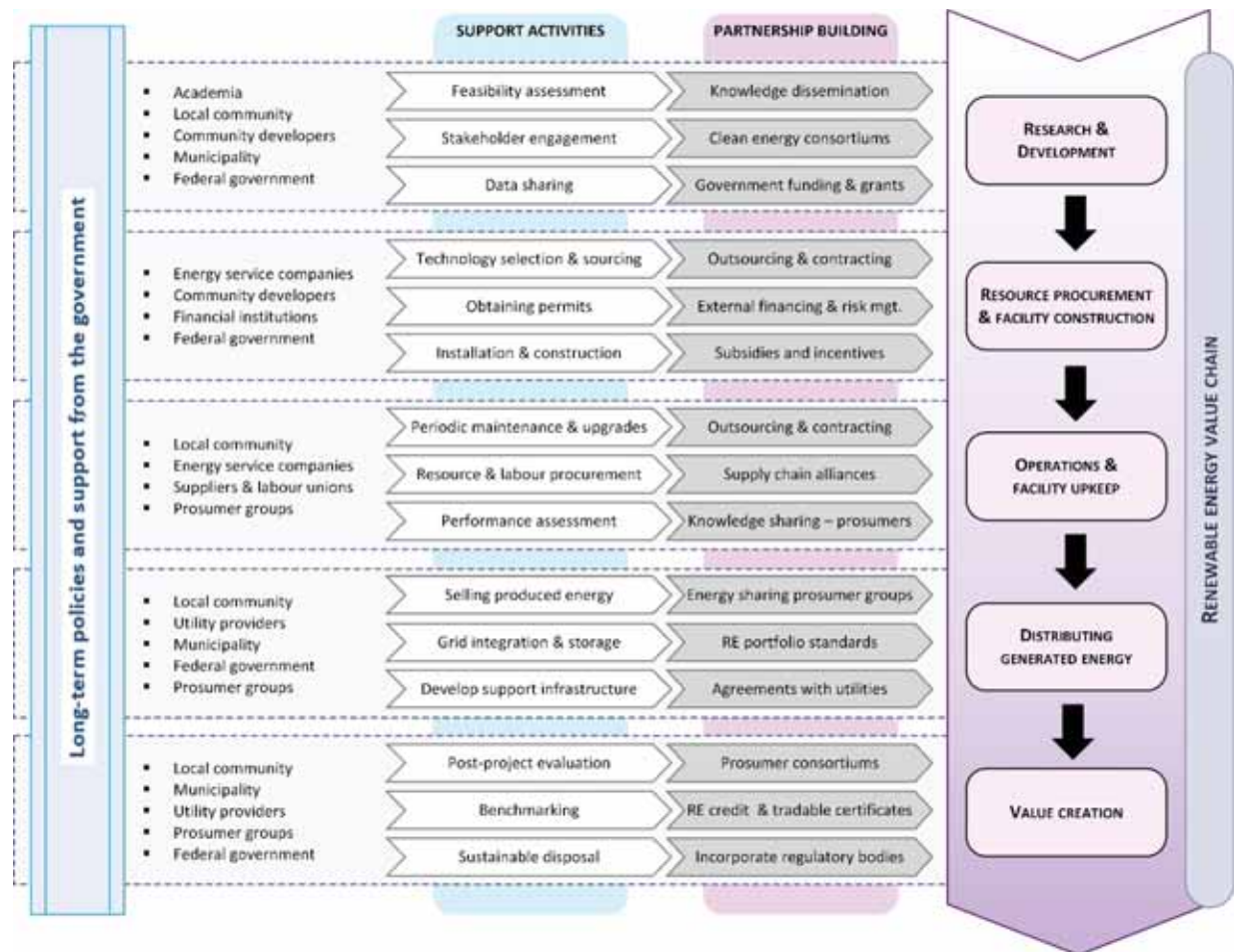


Fig 4: Integrated roadmap for value chain management in RE projects

The concept of value chain developed by Michael Porter in 1985 details the process in delivering a product or a service to the market [61]. This concept was adapted to describe the activities in RE project delivery in the roadmap. RE projects start with research and development for concept initiation, and ends with value creation, not only for the RE producers directly, but also for the local community and the surrounding region. If successful, RE projects can contribute to job creation and infrastructure development, and in the long run, to the local economic development [14]. At each stage of the value chain, a different set of stakeholders are involved, who need to join together in the partnering framework for the success of the RE project. Each stage has a set of support activities which need to be carried out. One of the key support activities which is critical to the success of most value chain activities is sharing of pertinent data and information among stakeholder groups and similar communities. An integrated data sharing platform, which can keep records and accommodate real-time updates on community information and energy system performance, is suggested as a solution to the lack of knowledge and experience that plagues many

communities when pursuing RE deployment. Real-time data sharing has been used in other contexts such as the use of Building Information Modelling (BIM) databases in construction industry, to learn from prior projects to ensure maximised outcomes in the next projects [62]. Similarly, a community can make use of the lessons learned in RE project deployment in another community to ensure better results for their own and avoid making the same mistakes. Integrated and interactive data platforms can also be the initial step in developing regional energy consortiums among key stakeholder groups. As previously mentioned, this mechanism is an integral part of risk sharing. Partnerships can also assist in providing solutions to the uncertainties and resource limitations inherent in RE systems. Prosumer groups can agree to share energy among themselves, and arrangements with utility providers can further assist communities in safeguarding their supply reliability and energy security while shifting to RE. Further, partnering alliances made with energy service companies, consultants, and academia would provide communities with the expertise and technical knowhow required to assess and implement RE projects. Thus, partnership building is required for

connecting the value chain activity steps with the necessary support activities in practically realising RE projects. Long-term policy support from the government is the vital component in achieving all of the above. The policy support should not only remove the barriers towards RE penetration, and incentivise RE investment, but should also encourage the development of partnerships and consortiums for promoting RE.

6. Conclusions and future work

While RE is being hailed as the future of energy systems, a multitude of barriers and challenges exist in the deployment of RE projects in their current form. These problems have prevented large scale commercial utilisation of RE, which runs contrary to the goals of emissions reduction as well as increased energy independence and energy security for communities. The proposed partnering framework discusses a way forward in delivering RE projects while solving the issues and exploiting opportunities. Sharing information, knowledge, and expertise among stakeholder groups and different communities can help in lowering the hurdles and minimising the risks. Partnering also opens up more opportunities for communities and other stakeholder groups. Strategies which have been successfully implemented in similar contexts such as the energy efficiency sector can be adapted to RE project management using a partnering approach. Regulations and policy support act as the glue in holding together the efforts of RE project deployment by various parties, and help to achieve goal congruence among stakeholders. Therefore, the government needs to spearhead the endeavour to develop a comprehensive partnering framework for RE project risk mitigation.

Eliciting stakeholder opinions on the challenges and opportunities in RE project deployment can lead to a better understanding of the concerns of key stakeholder groups, and can lead to the delivery of more suitable solutions in the future. Public engagement of stakeholders through surveys and interviews, as well as developing common engagement platforms (e.g. discussion forums, conferences) headed by neutral groups such as universities can assist in obtaining stakeholder inputs effectively. Further work needs to be done in this direction to conduct more public engagement activities and knowledge dissemination. Ultimately, this work can lead to the development of energy sustainable communities across Canada, while strengthening the Canadian energy sector considerably.

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Development of a Framework for Sustainability Management in the Construction Industry Approaching Both Organizational Structure and Processes Management

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Abstract:

The construction industry faces considerable challenges with sustainability issues due to the significant contribution to environmental and social impacts of this field. The diversity of standards, certifications, and other materials for helping to consolidate and approach sustainable practices in this area makes task management arduous and affects the way that construction projects are managed. Moreover, it is challenging to translate broad sustainability goals into specific and clear targets in the construction field. This study considers two levels of project management: the level of organizational strategy—called Sustainability Organizational Practices, *SOP*, in this research—and the level of specific management practices—called Sustainability Management Processes, *SMP*, here. First, to assist translating the broad sustainability goals into specific targets, this research performed a meta-analysis study considering a large number of rating systems and international sustainability organizations framework for identifying the sustainability indicators in the construction field. The indicators were analyzed according to the Sustainable Development Goals of the United Nations and categorized according to the quadruple perspectives of sustainability management: economic, environmental, social and ethical. Second, to develop a framework for sustainability management for the construction industry, this research analyzed various management models such as business models, project management models, construction management models, sustainability management models, sustainability management standards, and sustainability rating systems. Third, to identify the connection between the *SOP* and *SMP*, this research interviewed eight professionals from four different construction organizations. In conclusion, this study provides an understanding of sustainable impacts of the construction field through sustainability indicators and a framework for sustainability management for the construction industry approaching both organizational structure and process management.

Keywords:

Sustainability management framework, sustainable development goals of the construction industry, sustainability organizational practices, sustainability construction indicators, sustainability management model for the construction industry.

1 Introduction

Since the United Nations Conference on the Human Environment, held in Stockholm in 1972, sustainability has been a major focus of discussion. The term has become a political and ethical argument for addressing the ecological and social crises of the world. The constant observation of these ecological and social crises demonstrates the connection between the environment and human beings (behaviour). The World Commission on Environment and Development (WCED) presented in 1983 the most popular sustainable development interpretation: to meet the needs of the present generation without compromising the ability of future generations to meet their needs [1].

Now, sustainable development engages further complex issues such as economic development models, the world food supply, poverty reduction, justice, and also nature conservation [2].

The way an organization addresses sustainability issues impacts, not just the environment, but also employees, nearby communities, clients, and material

sources. Consequently, a focus on sustainability management is important to all types of organizations.

Moreover, although the initiative to implement sustainability in daily operations starts with a desire to impact the world positively, organizations are detecting the benefits of sustainable practices such as to reduce costs and to improve corporate image [3].

Furthermore, there is an excessive number of articles and standards that describe different interpretations of sustainability and sustainability practices across diverse fields. However, the diversity of studies makes it hard to consolidate an approach, justifying the lack of understanding and yet the difficulty of implementing sustainability management into the daily operations of the organization.

Hence, collecting and implementing the different approaches have become an increasingly burdensome management task.

Construction projects are very complex. They require the involvement of many different stakeholders and contribute significantly to the environmental impacts [4]. Consequently, to address the complexity of

sustainability management in construction, it is essential to apply a management system approaching: an understanding of the responsibilities' distribution; identification of the key positions; identification of the management levels; and a definition of the relationship of the departments [5].

The first objective of this study is identifying the impacts and sustainability indicators relevant to the construction industry through an extensive literature review of sustainability issues and a meta-analysis study of sustainability indicators in the construction field. The second objective is developing a framework for sustainability management in the construction industry approaching both organizational structure and processes management (in this research, we call these two layers Sustainability Organizational Practices—SOP—and Sustainability Management Processes—SMP—respectively). The third objective is identifying the connection between these two levels through interviews with four different organizations.



Fig 1: Sustainability Construction Management. The figure represents the sustainability construction management system evaluated in this study.

This study approached normative documents such as the international standards for environmental management (ISO 14000 family) [6], the general principles of sustainability in building construction (ISO 15392) [7], the guidance on social responsibility (ISO 26000) [8], and assessment management standard (ISO 55000 family) [7]. It also studied the sustainability rating systems such as Leadership in Energy and Environmental Design (LEED) [9], and Rating System for Sustainable Infrastructure (ENVISION) [10]. Management systems such as PMBOK [11], sustainability management MBA, sustainability assessment, organizational structure,

and stakeholders' management are also the focus of the literature review.

2 Sustainability Construction Indicators

The Global Sustainability Standards Board (GSSB) suggests that indicators provide information on the performance of an organization that reflect the social, economic, and environmental impacts. Also, the indicators provide information to influence and assist decision of stakeholders [12].

Initially, this research conducted a study of normative documents and sustainability rating systems of measuring sustainable practices that the construction industry can influence, impact, and manage.

Followed by a meta-analysis of documents such as Sustainability Impact Assessment-SIA [13], International Chamber of Commerce-ICC [14], Sustainable Master Business Administration (MBA) [3], Agenda 21 [1], Sustainable Development Goals-SDG [15], World Business Council for Sustainability Development (WBCSD) [16], Leadership in Energy and Environmental Design (LEED) [9], ENVISION [10], Green Globes [17], Sustainable Project Appraisal Routine-Spear Arup [18], ISO family [7], and Global Reporting Initiative [12].

From these references, this study collected a total 105 indicators among environmental, social, economic and ethical categories. Through mapping these indicators to the 17 international Sustainable Development Goals - SDGs (United Nations, 2015), we reduced the list to 99 indicators.

In summary, this research identified 99 sustainability indicators in the construction field correlated to the United Nations' SDG and categorized into the Economy/Environment/Society/Policy quadruple of construction sustainability management.

3 Framework for Sustainability Management in the Construction Industry

Construction management activities can be organized into six hierarchical levels: organizational, project, activity, operation, process, and work task level [19].

Moreover, there is more than one way for a company to define its strategies, objectives, structure, and processes. However, it is crucial to create a framework that helps the organizations achieve their objectives based on basic patterns [20].

This research conducted a study of management systems through a literature review to identify the main system levels to elaborating the proposed framework.

Based on the sustainability management investigations, a conceptual model was developed focusing on both an organizational structure and a

process management for sustainability management in construction, illustrated in figure 2. Section 3.1 describes the SOP elements of the framework while section 3.2 discussed the SMP components.



Fig 2: Sustainability Management Framework for the Construction Industry. The figure represents the proposed framework for sustainability management.

3.1 Sustainability Organizational Practices - SOP

At the organizational level, we evaluate from a business management perspective. The definition of the organization's mission and its purpose can define objectives of key areas. The balance of these objectives converts objectives into concrete strategies and resources' allocation [21].

The organizational structure arises from an ongoing process of evaluating the organization purposes –

questioning, verifying, and redefining the manner of interaction with its environments [22]. Hence, the idea of the SOP is to introduce the main processes that the organizations can focus on and repeatedly update for articulating their sustainability goals and establishing mechanisms for achieving them. The following sections organize these processes into four broad categories: Drivers/Goals, Targets (objectives), Team, and Policies/Practices. Each process is described regarding its inputs, tools, and outputs.

3.1.1 Drivers / Goals

As sustainability issues have evolved, sustainability practices have increased their needs and value. Clear and simple organizational drivers (rather than just intuition) allow organizations to endure and grow for a long time. Only a precise definition of *drivers* and purpose of the organization makes possible clear and realistic organization's objectives [21].

The SOP divides the drivers and goals of the organization into three parts: definition, promotion, and reporting. Table 1 describes the inputs, tools and outputs of these elements.

Definition

Defining the organization's drivers will help to identify the organization's goals, including people, knowledge, and conditions (such as market forces) that initiate and support activities for which the business was designed [23].

Promotion

The internal communication establishes a service orientation focusing on achieving effective internal exchanges between the organization and its employees [24]. Moreover, internal communication

Table 1: Drivers and Goals – Input, Tools, and Output

Drivers and Goals: Definition		
Inputs - Market: client types - Knowledge & values: market's sustainability requirements.	Tools - Sustainability Practices Analysis - Categories: sustainability practices by category - External regulations and policies - UN sustainability goals - Organization's sustainability focus.	Outputs General Sustainable Goals (GSG): for each category
Drivers and Goals: Promotion		
Inputs General Sustainable Goals (GSG)	Tools - Sustainability Promotion Analysis - The content of the information - Recipients - Format of divulgation	Outputs Organizational Sustainability Values Promotion (OSVP)
Drivers and Goals: Reporting		
Inputs General Sustainable Goals (GSG)	Tools - Sustainability Values Reporting Analysis - Organization's Activities Impact/Influence - Yardstick Measurement - Objective/ Strategy - Report Frequency - Results – presentation format	Outputs Sustainability Organizational Report (SOR)

affect employee work attitude [25], promoting awareness of its environment, a sense of belonging to the organization, an understanding of its evolving aim, and a commitment to the organization [26].

Reporting

The sustainability report demonstrates the economic, environmental and social impacts caused by the organization's activities and present the organization's values and governance model, linking its strategy and its commitment to a sustainable global economy [12].

3.1.2 Target

The objectives of an organization need to be performance objectives aimed at doing rather than at good intentions [21]. A clear definition of what the organization desires to achieve is essential for organizing its structure and strategies. Therefore, this research focused on the stakeholder's analysis to identify the sustainability targets of the organization.

The SOP divides the effecting of the target of the organization into three parts: stakeholders' identification, approach, and goals. Table 2 describes the inputs, tools and outputs of these elements.

Stakeholders' Identification

To identify and prioritize the stakeholders of an organization is a very important tool to determine its targets. The framework for stakeholder's identification based on three attributes—power, legitimacy, and urgency—can help the organization to determine the priority of its stakeholders [27]. This research considered the power (importance) and legitimacy (influence) to determine the priority stakeholders.

Stakeholders' Approach

The stakeholder analysis determines the qualitative and quantitative information to take into consideration to identifying the interests, expectation, and influence of the stakeholders [28].

Stakeholders' Goals (Sustainability Goals)

Following the sustainability stakeholders approach, the organization can determine its sustainability goals/target and their target date.

3.1.3 Team

The analysis of work consists of four steps. First, to identify all operations necessary to produce a known end. Second, to elaborate a rational organization of the sequence of the operations and workflow making it more manageable, smoother, and more economical. Third, to analyze the individual operation including the appropriate tools, the required information, and materials. Fourth, to integrate the operations into individual jobs [21].

The SOP divides the effecting of the team analysis into three parts: knowledge and skills, roles, and organizational structure. Table 3 describes the inputs, tools and outputs of these elements.

Knowledge and Skills

The roles and responsibilities will provide information for defining the positions, skills, knowledge, and competencies needed to assist the human resources to identify, and eventually release team members [29].

Table 2: Target – Input, Tools, and Output

Target: Stakeholders' Identification		
Inputs - Categories: sustainability practices by category (economic, environmental, social, and ethical) - Geographic Sphere: market location - Stakeholders List	Tools - Stakeholder's Identification Analysis - Stakeholder Matrix: to identify the importance of each stakeholder - Priorities Stakeholder	Outputs Organization's Sustainability Stakeholders (OSS)
Target: Stakeholders' Approach		
Inputs Organization's Sustainability Stakeholders (OSS)	Tools - Stakeholder's Approach Analysis - Potential strategies - Limitations - Chosen Objectives	Outputs Organization's Sustainability Stakeholders Strategy (OSSS)
Target: Stakeholders' Goals (Sustainability Goals)		
Inputs Organization's Sustainability Stakeholders Strategy (OSSS)	Tools - Organization's Sustainability Goals Analysis - Target - Target Milestone - Target Review	Outputs Organization's Sustainability Targets (OST)

Table 3: Team – Input, Tools, and Output

Team: Knowledge and Skills		
Inputs Organization's Sustainability Targets (OST)	Tools Knowledge and Skills Analysis: - Required knowledge/Training/Certifications - Required Tools/ Activities	Outputs Sustainability Organizational Knowledge and Skills Document (SOKS)
Team: Roles		
Inputs - Organization's Sustainability Targets (OST) - Sustainability Organizational Knowledge and Skills (SOKS)	Tools Sustainability Roles Analysis: - Role/Level of the position - Department Analysis: a new department is needed? - Departments Interrelationship Analysis	Outputs Sustainability Organizational Team Document (SOTD)
Team: Organizational Structure		
Inputs - Sustainability Organizational Knowledge and Skills (SOKS) - Sustainability Organizational Team Document (SOTD)	Tools Sustainability Organizational Chart	Outputs Sustainability Organizational Chart (SOC)

Roles

The objective is to ensure that each work package has an owner and all team members have a clear understanding of their roles and responsibilities [29].

Organizational Structure

It is essential to identify sustainability management within the corporate structure: the roles, knowledge and skills required to determine the organization's sustainability model. To design the structure of an organization, Drucker [21] suggests responding to four questions. The first question is to identify the units of the organization. The second one is to determine the components that join together, and what components are apart. The third one is to define the size and shape of the different components. The fourth is to identify the appropriate placement and relationship of different units.

3.1.4 Policies & Practices

Policies delineate, specify, and authorize the methods that any institution is administered [30]. The policies assist the guidance of behaviours, transactions, initiatives, and protocols [31].

The SOP divides the effecting of the policies and practices into three parts: definition, promotion, and validation. Table 4 describes the inputs, tools and outputs of these elements.

Definition

Bandow and Hunter [32] identify several points that policymakers should consider when creating the policy. Some of these points are defining a committee member to evaluate the policy frame. Also, to determine the expected behaviour, to identify the related local, state, and federal law, to describe the expected behaviour and responsibilities of managers and employees, and to determine the informal and formal complaint procedures.

Promotion

The implementation of any policy by all relevant parties in an organization is as important as the creation of that policy.

Validation

It is essential to evaluate the effect and receptivity of the team for each policy making sure it is applicable.

Table 4: Policies & Practices – Input, Tools, and Output

Policies & Practices: Definition		
Inputs General Sustainability Goal (GSS)	Tools - Sustainability Committee Analysis - Committee of sustainability policies analysis - Member's Roles: policy-maker, implementers, beneficiaries, evaluators, executors (to identify the department directly affected by the policy) - Values and Practices Analysis: - Values / Policy Goals - Departments related - Expected Behaviors and responsibilities - Remedies (in case of conflict) - Routinization: basic and daily behavior for each goal	Outputs General Policy Document (GPD)
Policies & Practices: Promotion		
Inputs General Policy Document (GPD)	Tools - Stakeholders' Analysis - Stakeholders - Stakeholder's description –level of knowledge - GPD's Promotion Plan - GPD's Plan - GPD's Validity - Communication Plan - Feedback Plan	Outputs GPD Promotion (GPDP)
Policies & Practices:		
Inputs - General Policy Document (GPD) - Feedback Plan	Tools - Policies Validation Analysis - Frequency Evaluation - Assessment Methodology - Improvements Plan - Policy Review	Outputs GPD Validation (GPDV)

3.2 Sustainability Management Processes - SMP

Engineers and Geoscientists BC's Code of Ethics requires integrating sustainability considerations into professional practices. It requires holding paramount the safety, health, welfare of the public, the protection of the environment, and promoting health and safety within the workplace [33]. Nevertheless, many certifications and regulations are requiring the implementation of sustainable practices.

The SMP determines the processes an organization may implement and repeatedly update, if necessary, on each project for articulating its sustainability goals and mechanism for achieving them.

3.2.1 SMP - Task Management

The following sections organize the processes into six categories of task management: processes, indicators, policies, communication, processes, assessment, and report management. Table 5 describes each feature of the SMP regarding its inputs, tools, and outputs.

Processes

Sustainability processes allow the organization to go from abstract or ethical goals to tangible and practical

actions. Applying sustainability practices into process management contributes to the progress of the society, economy, and environment [34].

Indicators

Project management requires a reliable mechanism to ensure that the performing agencies monitor and control the project plan's objectives [35].

Policies

The International Chamber of Commerce (ICC) created the Green Economy Road Map to assist business in the development of sustainable policies and reinforce the importance of innovation, collaboration, and governance from both bottom-up and top-down [14].

Communication

A communication plan is vital to motivate, inspire, and guide employees [36].

Assessment

Assessment management involves reporting the sustainability performance and the progress of the organization. It is also a valuable tool to aid in the shift towards sustainability [37].

Reporting

Reporting performance is the process of collecting and disclosing performance information including the status report, progress measurements, and forecast. It considers the management plan, the performance information, the measurement methodology, the estimates and progress assets [28].

4 Interviews

This study interviewed four organizations and eight different professionals at different management levels. The profile of the organizations were as follows.

- Company A
This research interviewed the project manager, project coordinator, construction superintendent, and site safety officer. The organization applies LEED if

Table 5: SMP – Input, Tools, and Output

Tasks Management: Processes		
Inputs • Activities Definition • General Sustainable Goals (GSS) • Organization's S. Targets (OST) • Sustainability Organizational Team Document (SOTD)	Tools - Sustainability Processes Analysis • Stakeholders - internal and external • Self Assessment - sustainability impact of each activity • Indicators • Tools - physical (equipment), intellectual (specialist), or technological (system) necessary to execute the activity • Benchmarking/ Performance Case	Outputs • Sustainability Process Document (SPD)
Tasks Management: Indicators		
Inputs • Activity • Sustainability Indicators	Tools - Sustainability Indicators Analysis • Indicators Identification: the intent, description, level of achievement, metric and the document of evidence for the performance	Outputs • Sustainability Indicator Document (SID)
Tasks Management: Policies		
Inputs • Sustainability Process Document (SPD) • General Policy Document (GPD)	Tools - Policies Analysis • Conditions – To develop short and clear high level of conditions for each sustainability process of each activity • Actions Plan • Collaborative Actions –internal and external stakeholders • Principles - best practices	Outputs • Sustainability Practices Document (SPrD)
Tasks Management: Communication		
Inputs • Sustainability Practices Document (SPD)	Tools - Sustainability Communication Analysis • Communication Plan: clear and consistent message to educate the employees	Outputs • Sustainability Practices Communication (SPC)
Tasks Management: Assessment		
Inputs • Sustainability Indicator Document (SID)	Tools - Sustainability Assessment Analysis • Analysis –proposal and scope of the indicator • Delineation –methodology to assess the indicator • Impact Analysis – to identify the impact and conflicts of each indicator • Optimization – to elaborate a mitigation plan	Outputs • Sustainability Assessment Document (SAD)
Tasks Management: Reporting		
Inputs • Organization's Sustainability Targets (OST) • Sustainability Indicator Document (SID)	Tools - Sustainability Report Analysis • General Standard Disclosures – organizational profile, strategy and analysis, opportunities and limitations, stakeholders engagement. • Specific Disclosure – to identify the indicators, their approach and the desirable performance	Outputs • Sustainability Report Document (SRD)

the client requires, otherwise it implements regulatory mandated sustainability practices. Although the company has sustainability policies, they are not promoted to the construction team. Only the project manager was trained with the organization's sustainability values and policies but did not expand to the rest of the team.

- Company B.

This research interviewed the project manager and LEED coordinator. The organization has a specific sustainability department to manage the sustainability practices of the projects. However, it is limited to LEED indicators and methods.

- Company C

This research interviewed the project manager. The organization applies LEED in its projects and has sustainability values and policies. Although there is no formal training, the sustainability values and policies are promoted to the construction team through messages in the intranet and formal documents

- Company D

This research interviewed the project manager. The organization does not have any sustainability policy and follow the practices required by law, only.

For this research, the interviews were conducted and analyzed with the objective of identifying the way the organizational structure (SOP) can influence the professional's behaviours (SMP).

The questions intended to identify the way the organizations require sustainability practices and the way the professionals reacted to or perceived the importance of sustainable practices.

Furthermore, the questions were divided into two categories: the organizational structure and the processes management. The objective was, first, to identify if the organization has sustainable policies and the way these are promoted to the construction team. Second, to determine the way the interviewee responded to the sustainable practices.

The primary results are discussed on the next topic.

5 Results and Discussion

First, this research identified 99 sustainability indicators from the meta-analysis study highlighting the way the construction industry can contribute to the sustainable development goals. These 99 sustainability indicators are categorized according to the quadruple of sustainability management and contribution to the 17 development goals [38], represented in Figure 3.

Second, this research suggested a framework for sustainability management for construction industry approaching both the organizational structure and the processes management, called SOP and SMP respectively. The proposed framework considered important context from different models in the

literature review identifying the way the organization can efficiently implement the sustainability management into these two management levels.

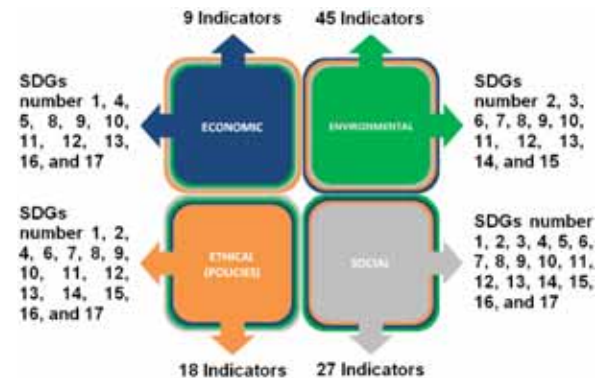


Fig 3: Quadruple of Sustainability Management in the Construction Field. The figure represents the four categories of the indicators and the addressed SDG.

Furthermore, the framework might also indicate the connection between the organizational structure and the processes management level. Once the conceptual model was carefully designed to identify the critical inputs and outputs for each feature of the framework, this research identifies a plausible connection between the SOP and the SMP. The information that the SOP provides to the SMP can illustrate this relationship. Figure 4 demonstrates these documents

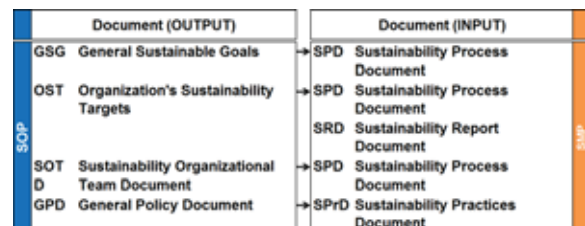


Fig 4: SOP and SMP's documents. The figure demonstrates the SOP documents that provide input to the SMP documents

Third, this research interviewed eight professionals in four different construction organizations to identify the way the organizational structure (SOP) can influence the professional's behaviours and processes (SMP). Based on the interviews, this research can highlight the following observations and hypotheses:

- In company A, the project manager received training and acknowledges the values and policies of the organization. Her sustainable behaviour was noticeable. However, the Project Coordinator, Construction Site Superintendent, and Site Safety Officer did not know the sustainability policies and sustainability values of the organization. They mentioned that they would follow the processes

that the project manager determined and that it was obligated. The principal researcher did not perceive a behaviour changing and a lack of involvement in the sustainable development and sustainable practices were visible. The researcher observed the importance of having a transparent sustainability organizational structure and promoting the values and goals of the organization to implement sustainable behaviours into its employees at all levels. The SOP assists to do that.

- In company B, the organization has a specific department for controlling the sustainability practices of its projects. The group was structuring its sustainability practices, and it did not yet have well-defined values and policies following the LEED practices. However, it demonstrated that, although the employees acknowledge the standard, they did not recognize the organization's values. The lack of sustainability organization values demonstrated, again, the importance of the employees' involvement in the sustainable development and the promotion of the sustainability organizational structure to the team at all levels. SOP assists to do that.
- In company C, although the project manager did not have any specific training in sustainability or additional certification such as LEED membership, the professional was involved and desiring to improve the sustainable processes because the organization continually promote its values and policies. The researcher observed that, even though the professional did not have a sustainability background, the sustainability practices were incorporated into his behaviours because the organization's sustainability goals were transparent to the team. It demonstrated the impact of promoting the organizational sustainability values to the team at all levels. That is the purpose of the SOP and SMP.
- In company D, the organization did not have any sustainability policy or certification to follow. The project manager could not answer any question related to sustainability management other than the ones that are obligated by law.

6 Conclusions and Outlook

This research provides an understanding of sustainable impacts of the construction field through sustainability indicators demonstrating how the construction industry can efficiently and practically contribute to sustainable development. The proposed framework approaching both organizational structure and process management intends to assist the organization to elaborate its values, policies, procedures, and structure for sustainability management, creating a tangible model to implementing sustainability management in the construction industry.

Further studies are required to identify the best practices of each feature of the framework assisting

the organization to implement sustainability management processes.

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Installation of Charging Infrastructure for Electric Vehicles in Multi-Unit Residential Buildings in British Columbia

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Abstract:

Electric Vehicles (EVs) contribute to the mitigation of climate change through reduced greenhouse gas emissions, when powering with sustainable sources of electricity. The province of British Columbia (BC) is an attractive location for EV deployment since most of its electricity is sourced from clean renewable energy sources. Due to their driving range and potential to reduce local emissions, EVs work well in urban contexts, where most residential buildings are located. As a result, residents from Multi-Unit Residential Buildings (MURBs) are among those interested in becoming EV owners, thus requiring access to charging infrastructure, especially overnight home charging, which is the preferred charging alternative. However, most residential buildings are not equipped with charging infrastructure and its installation can have numerous challenges that can turn into barriers. This study aims to explore the implications and challenges involved in the process of EV charging infrastructure installation in MURBs. By identifying present and future barriers to infrastructure provision, potential policy actions to address them can be recommended.

Keywords:

Electric vehicles, EV charging infrastructure, residential buildings.

1. Introduction

Electric vehicles (EVs), as an alternative to traditional fossil fuel vehicles, have become a reality for many countries including Canada. EVs contribute to the reduction of fossil fuel dependency of the transportation sector, as well as the improvement of air quality and mitigation of climate change through reduced greenhouse gas emissions [1], [2]. Since the first EV sold in Canada in 2011, the market has been growing and sales have been increasing significantly as manufacturers release new models, and consumer understanding and trust of the technology continues to increase [3].

Powering EVs with sustainable sources of electricity has added benefits in terms of sustainability metrics [4]. The Canadian province of British Columbia (BC) is considered as one of the most attractive locations in the world for EVs since 85% of its electricity is sourced from large hydropower, a clean renewable energy source [5]. In addition, current residential electricity rates in this province means the cost of charging a vehicle at home is less expensive than fueling a conventional vehicle with gasoline [6]. BC is also the province with the third highest EV sales in 2017, as well as the second highest increase in the adoption rate, a 48.6% increase over 2016 [7].

EVs, understood in this study as light-duty vehicles partially or fully fueled by grid electricity, have the commonality of having to be plugged in to charge the vehicle's battery pack. Charging can be made possible in workplaces and public spaces, but research suggests that 80-90% of charging happens

at home where it is most convenient for drivers [3]. Due to their driving range and capacity to reduce emissions significantly, EVs fit well in city contexts. Thus, there is growing interest from vehicle drivers in cities, including residential building inhabitants, to have access to EV charging infrastructure, which is considered a prerequisite to EV ownership [3].

For these reasons, the deployment of charging infrastructure in residential buildings in BC (also known as Multi-Unit Residential Buildings or MURBs), has been receiving attention recently from the provincial and municipal governments and from residential building associations. These groups have recognized the importance of home charging in promoting EV adoption, but also the fact that achieving charging infrastructure access in MURBs has an additional layer of complexity compared to detached homes. Installing new infrastructure in existing buildings has numerous implications and barriers, which can hinder the installation of charging infrastructure in MURBs.

This study aims to explore the implications and challenges involved in the process of EV charging infrastructure installation in MURBs. By identifying present and future barriers to infrastructure provision, potential policy actions to address them can be recommended.

2. Problem dimensions

The problem of EV charging infrastructure installation in MURBs in BC was analyzed from three different perspectives or dimensions: EVs and charging

infrastructure, existing MURBs, and regulations and policy. These dimensions were mapped on a Venn diagram (Figure 1) to analyze the intersections among them.

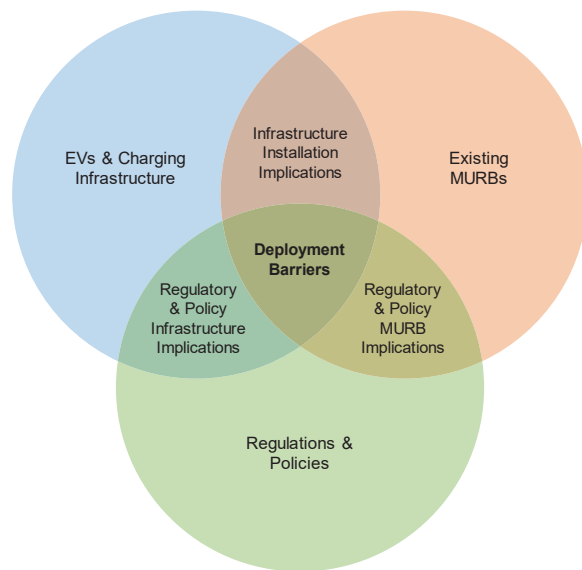


Figure 1 Venn diagram framework

First, the EV types included are only the Plug-In Electric Vehicles which can be partially or fully fueled by grid electricity [3]. This includes both plug-in hybrid electric vehicles (PHEVs) and battery electric vehicles (BEVs) but excludes hybrid electric vehicles (HEVs) because they do not have the capacity to be plugged in and charged with electricity from the grid, and therefore do not need nor benefit from the electric charging stations. The EV offer in Canada is quite comprehensive. There are currently 15 different models of BEVs and 26 models of PHEVs [7]. BEV sales in BC exceed the PHEV sales by more than double, mainly led by the Tesla models (only available as BEVs) which account for more than 40% of the total BEV sales in the province [7].

Regarding charging levels, there are three levels of EV charging: Level 1 (Opportunity), Level 2 (Primary) and Level 3 (Fast) [8]. There are also two types of charging infrastructure, public and private. Public charging infrastructure includes the charging stations that are available for use to the general public and are publicly accessible. Public infrastructure is useful for EV owners that need additional charging during the day or that don't have access to overnight charging at home. As EV sales increase, so does the network of charging stations. There are currently around 1,000 public charging stations in BC, most them being Level 2. Private charging infrastructure refers to the charging stations located on private property and not available for use of the general public. Private charging stations are usually located on home or

office premises and can only be used by the station owners (in the case of households) or other authorized personnel (such as office employees). Private charging infrastructure is usually Level 1 or Level 2, since Level 3 works on DC and is not currently considered viable and safe for installation within residential buildings. The decision between Level 1 and Level 2 installation depends on several factors, among them the user's charging needs and daily driving range, the EV model they own, the cost they are willing to invest for charging infrastructure, as well as the desired location and existing electrical system where the charging station will be installed.

Second, the term "existing MURBs" refers to buildings in the operation phase for which EV charging infrastructure was not installed during the construction phase. In B.C. there are mainly two types of MURB ownership: purpose-built rental buildings and strata or self-owned buildings. Depending on the type of building, the decision of installing charging stations is handled differently. In purpose-built rental buildings, tenants can request the installation of a charging station in their parking stall to the landlord or property manager and the decision relies on them. Strata buildings, on the other hand, have strata councils that can vote on the decision and the majority is achieved usually with 75% of the votes. In both cases, if the request is approved, agreements, bylaws, and rules may need to be put in place.

MURBs can also be classified as either traditional buildings or green buildings. Although green buildings are more likely to have had charging infrastructure installed during construction, this is not necessarily a rule. For instance, the LEED V4 for New Constructions (NC) standard, in its Green Vehicles credit, requires the designation of 5% of all parking spaces as preferred parking to EVs and install EVSE in an additional 2% of all parking spaces [9]. However, not all building developers will pursue this credit as it is optional and not a prerequisite, and even if they did, prioritizing only 7% of parking spaces for EVs might not be sufficient in the future. Because there is no requirement to prepare the building for future infrastructure needs, LEED-certified green buildings might face similar challenges as traditional existing buildings.

The electricity produced by the electric utility—in this case, BC Hydro—is fed through a meter, into the building, and is distributed to units and other areas by the building's power distribution system. The particular characteristics of each system vary among buildings, but the current BC Building Code and other applicable City Bylaws govern the overall design.

Third, it was observed that regulations and policies play an important role in the deployment of charging infrastructure in MURBs. Conventional fossil fuel vehicles have been on the market for over 100 years and have established a clear market lead relative to

other Alternative Fuel Vehicles (AFVs), which could be defined as a case of technological lock-in [10]. EVs as an emerging technology can benefit widely from external private and public support. Governments, through policy instruments such as regulation, taxation, subsidies, and incentives have helped shape the current EV market globally. Other initiatives such as setting long-term goals and providing R&D funding further support EV and infrastructure technical development [10]. The role of policy around EVs has been studied in more detail recently to enable the understanding of its potential influence and overall relevance in encouraging EV market development and diffusion. The methodology of these studies usually consists of creating or using models that forecast EV uptake based on several factors, and then perform policy analysis to measure the effects certain policies could have compared to a base case “no policy” scenario.

An example is a study conducted by Wolinetz and Axsen [11]. According to them, a large-scale transition to EVs is likely to require strong government support.

3. Problem dimensions intersections

From the Venn diagram, there are four intersections between the three main dimensions. First, the interaction of EVs and MURBs is modeled through the installation of charging infrastructure into the building electrical system. This new concept emerged from the commercialization of EVs, and the fact that these vehicles can be charged at home using grid electricity as other appliances do. New buildings are increasingly including the installation of charging infrastructure during construction to be “EV-ready” and provide charging infrastructure to its residents. However, existing buildings don’t have the same opportunity and, in turn, should make adaptations to the existing building system.

Regarding the characteristics of the charging infrastructure that can be installed, the levels of charging available for residential building are Levels 1 and 2. Level 1 charging can be considered sufficient for PHEVs, which have a shorter electric range and therefore a smaller onboard battery pack. However, this is not the case for BEVs that rely only on their onboard battery pack to operate, which would take between 11 and 36 hours to fully charge on this charging level. In addition to this limitation, BEV adoption in BC is approximately the same as PHEV adoption (excluding Tesla BEVs that use fast-charging methods). Therefore, it is preferable to install Level 2 charging infrastructure in MURBs to accommodate the needs of both BEV and PHEV users. As reviewed previously, there is also a general preference from all EV users to achieve a full charge faster than what Level 1 can offer. As technology evolves and battery capacity improves, faster charging will be prioritized.

The second and third intersections are the implications of policy and regulations on EV charging stations and on the existing MURBs respectively. In terms of the EV charging infrastructure, there are standards and codes that regulate charging stations and their installation. The document that regulates EV charging stations in Canada is the Canadian Electrical Code, specifically the recently added Section 86 – Electric Vehicle Charging Systems. There is also another relevant rule within this code for new equipment installation in apartment buildings: Rule 8 - 202(3)(a)(d) of this code, in its Circuit Loading and Demand Factor section. New equipment installed into an existing building creates additional electrical loads to the system. According to this rule, the load of equipment installed in a common area of an apartment building (among them, the parking lot) should be continuous, as if the equipment was operating constantly. This is a conservative approach to ensure that overloading of electrical systems does not occur and the public is protected, but unrealistic since not all vehicles will begin and end charging at the exact same time, neither will all charge stations be continuously charging a vehicle [12]. Therefore, the calculated load of the new charging stations on the electrical system will be greater than the actual load. This can lead to unnecessary and costly upgrades in the building’s power distribution system, given that the parts of this system might need to be changed to allocate for the extra loads as calculated by this rule.

Regarding the existing MURBs, residential buildings in BC and their electrical systems are regulated by the 2012 BC Building Code based on the 2010 National Building Code of Canada. Each municipality within BC can also develop their own bylaws that address issues outside of the scope of the BC Building Code. For example, the City of Vancouver has its own building code known as the Vancouver Building Bylaw, which is more stringent than the provincial code. As reviewed, the City of Vancouver has included a provision in their Building Bylaw to provide charging stations for 20% of the parking stalls within MURBs and to make technical considerations to reach 100% in the future. Although this ensures that new buildings in this City will be suitable for charging EVs now and in the future, it does not address existing MURBs. In terms of green buildings, different standards, codes, and certifications and rating systems focus on mitigating the environmental impact of new and existing buildings. The most popular green building certification in Canada is LEED. Although LEED v4 for New Constructions (NC) does allocate credits to EV charging infrastructure as reviewed previously, there is no such consideration in LEED v4 for Existing Buildings Operations and Maintenance (EBOM). Therefore, there is no incentive for installing charging stations in existing buildings when pursuing a green building certification.

The center intersection, where all the dimensions interact, refers to the potential deployment and policy

barriers that can hinder the installation of charging infrastructure in MURBs. These barriers were analyzed and categorized using a framework based on Browne, O'Mahony, and Caulfield [13]. The comprehensive set of categories assist in the identification and organization of the potential barriers. The categories, as well as the potential barriers in each category are:

- **Financial:** cost of charging infrastructure and installation, and the cost of the building system upgrades
- **Technical:** building system limitations
- **Institutional and administrative:** governance issues
- **Public acceptability:** liability issues associated with EV installation, lack of support from non-users, and limited understanding of new technology
- **Legal and regulatory:** lack of regulation of rights and obligations of stakeholders, limited technical guidance, conservative regulatory requirements, and planning permission for charging points
- **Physical:** spatial building constraints and lack of parking within MURBs

The characteristics of these potential barriers, as well as the types of policies that could be used to solve them, were also analyzed. According to the timeline and significance criteria, all the barriers that were identified as short-term barriers were also judged to be of low significance. These are: 1) the governance issues that arise from charging infrastructure procurement and installation; 2) potential liability issues associated with EV installation; 3) limited technical guidance throughout the process, and 4) planning permission for charging infrastructure installation.

The medium-term barriers with the most significance (medium) include: 1) the cost of charging infrastructure and installation as an additional investment for users; 2) the lack of support from non-users, especially relevant within strata corporations; 3) the lack of regulation of rights and obligations of users, strata corporations and landlords; and 4) the conservative regulatory requirements, especially referring to the contingency in the Canadian Electrical Code. Other medium-term barriers with less significance are the limited understanding of the new EV charging technology and the lack of parking available for all the residents within their MURB (off-street parking).

The long-term barriers identified are considered of high and medium significance, and although they belong to different categories, they all refer to the implications of accommodating the additional loads and the EVSE in the existing building power distribution system. These barriers are 1) the actual building power distribution system limitations; 2) the cost of the building power distribution system

upgrades needed due to the limitations, and 3) the spatial building constraints.

The analysis also reflected that the most significant barriers are related to the financial and technical categories. Most of the other categories have a combination of medium and low significance barriers.

The level of implementation is predominantly local, which means that municipal governments can take relevant actions through policy and successfully address most of the barriers. The cost of building power distribution system upgrades is of high importance and it is likely that policies will come from the provincial government level (due to the economic scale of a potential financial incentive). While the government is the most likely to take action, associations can also play an important role in addressing these barriers, especially with regulatory, education and awareness policies that do not require a large financial investment.

The financial barriers naturally require financial and fiscal policies, but most barriers can be addressed through regulatory policies, which, as mentioned, do not necessarily require large investments, unlike the financial or tax incentives.

4. Conclusions

As EVs become a viable and clean alternative to light-duty conventional vehicles and the EV market in BC grows, new opportunities and challenges emerge due to the different fueling mode of EVs. Because they are charged with grid electricity, which can be sourced from households, the majority of EV owners want to charge their vehicles overnight at home for convenience. Making charging infrastructure available in MURBs is a new and complex process that has numerous technical, financial, social and regulatory implications. Therefore, the goal of this study was to analyze the implications of installing charging infrastructure for EVs in Multi-Unit Residential Buildings in BC to uncover present and future issues that can emerge throughout the process and to identify the actions that should be taken to address them.

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Maximum Affluence and Lifestyle: Definition and Implications for Environmental Impact Evaluation

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Abstract:

In this study a revised IPAT equation is developed in order to expose several ways that technology and infrastructure drive environmental impacts of individual behavior. Specifically, the affluence parameter (A) is expanded into three sub-parameters: rate of consumption (R), duration of consumption (D) and a lifestyle coefficient (Λ). Dissecting the affluence parameter in this way points to a variety of opportunities for civil engineers to reduce environmental impact through technology and infrastructure design.

Keywords:

Impact, Affluence, Transportation, Infrastructure, Consumption

1. Introduction & Motivation

Sustainability professionals and researchers are increasingly incorporating rebound effects into life cycle assessment, material flow analysis, and urban metabolism models. Rebound effects are typically modeled as demand fluctuations based on changes in supply cost. A commonly cited example is the increase in highway-based travel following the widening of a highway. The initial draw of less congestion and shorter travel times enables, or lowers the cost of, highway travel for more individuals. "Rebound" occurs when the resulting increase in demand eventually offsets, and sometimes exacerbates, the congestion relief that was to occur through highway widening.

The rebound effect is often cited as "Jevon's Paradox," referring to the 19th century British economist who documented how and why total coal use increased as coal-burning engines became more efficient. However, rebound is not a paradox so much as it is an inherent feature of pent-up demand suddenly made available by a technological or infrastructural change that lowers the per-unit cost of a resource or service.

Innovators and researchers claiming environmental benefits from technological or infrastructural change are increasingly being called to address the potential for rebound effects in their evaluations. Zink and Geyer [1] recently criticized the popular "circular economy" movement for largely ignoring rebound effects as a potential outcome of manufacturing efficiency efforts. They point out, for example, that the current market for refurbished cell phones, rather than contributing to reduced new production, has grown up alongside increased cell phone production. Their study claims that "the smartphone circular economy (how it is currently practiced) necessarily leads to rebound." They conclude that "rebound could be a

serious obstacle to creating meaningful environmental improvement."

As noted above, rebound effects have been widely uncovered in the transportation sector where mobility efficiency gains (either through energy efficiency or route improvement) have occurred alongside of an overall increase in the demand for travel (total miles) and resource consumption (total gallons of fuel). The evolution of fuel economy in US motor vehicles, charted in Figure 1, clearly displays this trend.

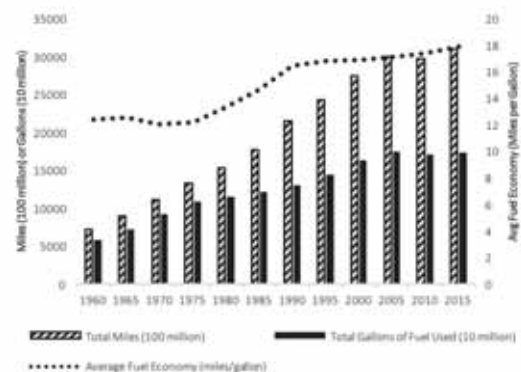


Fig 1: US Vehicle Travel, Fuel Use and Fuel Economy, 1960-2015 [2]

The latest generation of public infrastructure technologies must now be considered for their potential to reduce environmental impacts using the lessons learned about rebound effects. Miller and Heard [3], in discussing the positive and negative potential impacts of autonomous vehicles, point out that adoption trends will dictate whether this technology, and its supporting infrastructure, ultimately results in reduced per-capita transportation impacts. They note that "the environmental research community tends to focus on the technical aspects of

emerging products... however, behavioral adoption patterns have the potential to cancel the benefits of technical advances."

We turn to the question of how civil engineers, tasked with recommending and designing public infrastructure, can incorporate both rebound effects and behavioral adoption patterns into environmental impact assessment. We modify the IPAT equation (Impact = Population $\times$ Affluence $\times$ Technology), replacing A with three inter-related terms representing rate of consumption (R), duration of consumption (D) and lifestyle (Λ). The transportation sector is used as a test case.

2. Considering the IPAT Equation

In beginning to theorize about a comprehensive equation for robust impact assessment we began with the IPAT equation, originally proposed by Ehrlich and Holdren as a simple representation of the system of factors driving human-caused environmental change [4]. Since then, the equation has spawned several variations to correct for behavioral choices and societal influences [5, 6, 7] and is taught in college-level environmental science and policy courses [8].

Before modifying the IPAT equation we also consider the nature of the impact (I) we seek to track using this equation. We take the perspective of civil engineers contributing designs and insights to infrastructure in North America, where the task of mitigating global environmental impacts requires a stark reversal of per-capita consumption trends. Moore [9], for example, undertook a study of the per-capita ecological demands of citizens in Vancouver, Canada. She found that in order to align Vancouver lifestyles with long-term ecological carrying capacity, citizens would have to realize the following modifications: "73% reduction in household energy use, a 96% reduction in motor vehicle ownership, a 78% reduction in per capita vehicle kilometres travelled, and a 79% reduction in air kilometres travelled."

We take this as an extreme but valid demonstration of the great extent to which per-capita reductions in resource demand must be achieved. From a green civil engineering perspective, infrastructure must be focused on facilitating a significant downward shift of per-capita consumption so that aggregate impacts are also reduced, counteracting the effects of population growth and mitigating rebound effects. Our equation is thus focused on better assessing per-capita impact, or I/P. The following equation is the basis for our modifications:

$$\frac{I}{P} = A \times T$$

or:

$$\frac{\text{Environmental Impact Units}}{\text{Person}} = \frac{\text{Units of Demand}}{\text{Person}} \cdot \frac{\text{Environmental Impact Units}}{\text{Unit of Demand}}$$

Noting that the quantity of demand (A) and the environmental impact characteristics of the service/product demanded (T) may be highly linked, we focus on modifying the right side of the equation, ultimately incorporating more information about affluence and technology and still yielding a per-capita impact measure.

3. Modifying the Affluence Parameter

It is important to note that the Affluence parameter (units of demand per person) can depend highly on the type of technology being deployed. Were the average US driver to demand as many miles of automobile travel today as drivers in the early 1900's the per-capita impact of driving would have decreased by around 30%. However, a driver today travels much differently as a result of both technological and societal shifts over the past century. From a technological perspective, passenger vehicles today run on engines with at least seven times the power rating of a 1908 model T Ford [10]. Another way to say this is the average modern driver has the capability of doing seven times more travel-related work with their vehicle – in the form of distance traveled, comfort/safety features and amenities – per unit of time than the driver of over a century ago. Additionally, the total time that an individual may be required to draw on such high-power assistance has increased, as work and recreational activities have expanded further away from home [11, 12, 13].

We hypothesize that these two parameters – resource use per time (rate) and time spent drawing on such resources (duration) – are important underlying features of the true impact of technology deployment and usage. Thus, we A·T is replaced with R·D·T, the product of use rate, duration and impact per use, giving:

$$\frac{I}{P} = R \cdot D \cdot T$$

or:

$$\text{Environmental Impact} = \frac{\text{Units of Demand}}{\text{Time}} \cdot \text{Duration of Demand} \cdot \frac{\text{Environmental Impact}}{\text{Units of Demand}}$$

This separation of terms allows for consideration of how infrastructure and technology features ultimately affect impact. An example from the transportation sector is used to illustrate insights from making this separation.

4. Results and discussions

Appropriate units for transportation impact may be distance or energy. In this example, distance is used so that the rate (R) is in units of distance per time, or speed. Here the technological corollary is simple. The maximum achievable speed of transport, given technology type, may be used to estimate the upper

limit of potential impact from transport. Returning to the example of first-generation versus modern automobiles, the 1908 Model T had a maximum speed of 40 miles per hour, while the 2016 Nissan Altima, a highly popular sedan in the US, has an estimated top speed of 130 mph. If users of the two vehicles were to spend the same amount of time traveling per day at this top speed, the Altima driver would be responsible for 2.5 times as much fuel consumption as the Model T driver, despite the Altima's much-improved fuel-efficiency.

To further compare each transportation type's maximum possible impact, the maximum duration of travel must be factored in. Regardless of transportation mode, it is clear that travel in the 21st Century is conducted at higher speeds and for a longer duration than previously. The United States National Household Transport Survey [13] revealed that commuters spend an additional 10 minutes in a vehicle daily (59.8 minutes) compared to 1990 figures (50.7 minutes/day). Vale and Vale [14] examined travel habits in New Zealand's capital, Wellington, in 1956 and 2006 and found that the population had shifted its transportation time and habits dramatically to higher speeds of travel. Alongside this shift arose an increase in installed roads from .0005 hectares per person to .0023 hectares per person. As a conservative demonstration in our Model T-Altima example, we might estimate that the average Model T driver had a maximum duration of travel of 2 hours per day, while the Altima driver has a maximum duration of 4 hours per day, owing to modern infrastructural factors such as availability of fuel and roadways adapted especially for automobile travel. In this case, a doubling of duration leads to a total fuel consumption five times greater for the modern Altima as compared to the early Model T.

The Rate and Duration factors underlying Affluence reveal how technology and infrastructure influence impact. In a sense, technological and infrastructural designs have locked-in gradually greater levels of consumption by raising the ceiling on the potential resource consumption per person. This conclusion is evident from physical and technological parameters and does not necessarily require a discussion of regulatory or societal factors. However, we do add a lifestyle coefficient (λ , $\square$) signifying the fact that individuals will have varying demands for the full potential (rate and duration) of the technologies and infrastructure available to them. They may even deliberately adopt a low-lambda lifestyle, keeping total impact low relative to potential. Our final equation is:

$$\frac{I}{P} = R_{max} \cdot D_{max} \cdot \lambda \cdot I$$

This is simply the IPAT equation, where:

$$A = R_{max} \cdot D_{max} \cdot \lambda$$

Note that when $\lambda = 1$ "maximum affluence" occurs:

$$A_{max} = R_{max} \cdot D_{max}$$

This equation opens up several new possibilities for inquiry into the true nature of environmental impact from human activity. Instead of targeting simply Affluence, efforts to reduce negative per-capita impact can be focused on three different strategies: 1) Reduce the maximum rate at which technology utilizes resources, 2) Reduce the maximum duration for which resource consumption is allowed or desired and 3) Reduce lifestyle coefficients. These strategies exist in addition to the traditional technology-focused strategy of reducing impact per unit of consumption.

Civil Engineers interested in designing infrastructure that does not stimulate rebound and backfire might consider targeting the Rate or Duration aspects of the revised Affluence equation. Examples of design features that increase or decrease the maximum rate and duration of resource use in the transportation sector are proposed in Table 1.

Effect on Affluence Sub-Parameters	Rate (R_{max})	Duration (D_{max})
Increase	Increased engine horsepower and higher speed limits raise the overall rate of travel (distance per time).	Autonomous vehicle technology and infrastructure enables increased time spent in vehicles.
Decrease	Average speed lowered by speed bumps and other low-speed road designs .	Strategies for decreasing total time available for high-speed travel.

5. Conclusions and outlook

This examination of the IPAT equation's affluence parameter was motivated by a need to examine the contributions of technology and infrastructure designs to environmental impacts. Our focus has been on what the IPAT equation refers to as affluence (A), consumption per person. This structuring of the term masks the extent to which technological and infrastructural parameters drive individual consumption. By modifying A to be the product of consumption rate (R) and duration (D), it is possible to see that technological change determines the maximum possible affluence of individuals. As long as these parameters continue to rise, we risk the rebound of aggregate impacts following technological efficiency gain.

The accuracy of the modified affluence parameter depends on calibration of the lifestyle parameter, lambda (λ), which represents individuals' willingness or ability to consume at the maximum possible

affluence level. We intend to derive revealed lifestyle parameters from transportation data gathered in such surveys as the US National Household Transportation Survey. Furthermore, we hope to extend this methodology to other important sectors of civil engineering including water, energy and solid waste management.

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Investigating Residential Building Energy Consumption using Regression Tree Approach

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Abstract:

The management of energy consumption in buildings has become a critical issue in many cities around the world. Not only is significant socio-demographic changes and urban forms affecting directly, many cities are also witnessing that climate change leads to an alteration in energy demand. In this article, we estimate residential energy consumption model by employing a regression tree method while controlling two main categorical features in the residential building: the type of home and climate condition. Specifically, relative variable importance features are used to compare the importance among variables, which leverages the advantage of the hierarchical structure in regression trees. The results from models for the different type of home show that total square footage, the availability of natural gas in HVAC system, and climate condition have significant impacts on energy consumption. In addition, models controlling climate condition indicate that single-family homes are prone to be affected by socio-demographic factors such as income, household size compared to multi-family homes. The findings and modeling approaches in this study can contribute not only providing useful information with easily accessible information but also suggesting cost-effective modeling approaches.

Keywords:

Regression Tree, Variable Importance, Building Energy, Non-parametric statistical modeling

1. Introduction

Many cities around the world are actively trying to better control their demand for energy. In the past decades, substantial changes in climate and peoples' lifestyle have significantly affected energy consumption, especially in energy used in the building. In fact, buildings roughly consume 40% of all energy consumption in the United States and the EU (1–5). Specifically, the residential sector accounts for 21 % of total primary energy consumption and approximately 20% of total CO₂ emissions in the United States, which is more than the transportation and industrial sectors (2–4). Given these trends, developing effective strategies for managing consumption behaviors to substantially reduce building energy use is, therefore, becoming paramount. As a part of evaluating the impact of such policies, it is important to better understand what drives residential building energy consumption behavior under different residential settings and climate conditions.

Numerous studies have been conducted for addressing the relationship between building energy consumption and associated factors (e.g., climate,

demographic, building characteristics) that affect building energy consumption. In fact, the main distinction among the studies for building energy consumption is resulted from the type of factors and the type of modeling methods (e.g., parametric and non-parametric) (4,6–8).

Although applied statistical modeling methods using detailed and fine scale data can provide higher model performances, it is difficult to get highly detailed databases for energy consumption in general (4,6,8). Specifically, a model with the detailed information about building characteristics (e.g., size, vintage, construction type, etc.) can perform better in model prediction. It may be however limited to the small areas or specific cases that are available with the finer level of building information. Without such data, it would be difficult to directly investigate the impacts of the climate and lifestyle changes on the energy consumption. Cities and communities without access to such finer scale information will not be able to evaluate their policies and strategies for reducing building energy consumption.

In addition, parametric linear statistical methods (i.e., parametric linear model) have been widely used in

studies for estimating building energy consumption models (6,9,9–11). Despite the higher interpretability than others, previous studies have demonstrated that non-parametric statistical models (e.g., machine learning models) outperform the parametric linear models in modeling building energy consumption (8,12–14). It is because, in part, such machine learning (ML) models have fewer predetermined assumptions and better capture nonlinearities (e.g., interaction, stochasticity) about statistical relationships among variables.

Our study aims to estimate the residential building energy consumption model by using regression tree methods, which is a non-parametric statistical model applied to regression problems. Using an extensive national level residential energy consumption microdata database from the U.S. Energy Information Administration (EIA), we estimate models to investigate the properties and determinants of residential energy consumption for the different types of household and climate conditions. To enhance the applicability of the models, we purposely estimate the annual total energy consumption of residential building largely by using easily accessible information about household and its building characteristics.

We believe that our study can be used to fill the gaps where data resources are limited, and the preliminary analysis is required or preferred before moving into applied parametric models.

2. Methodology

A regression tree is a nonparametric statistical model used in regression problems by fitting models locally and then aggregating them together (i.e., additive modeling). Specifically, a regression tree partitions the entire data space (i.e., the set of the independent variable) into regions having the most homogeneous target values (i.e., responses) to independent variables (15). In addition, regression trees possess a key advantage in exploring the hierarchy of determinants that may affect a dependent variable (i.e., annual energy consumption). Specifically, this hierarchy also helps understanding the contribution of each determinant in predicting target values, which can be measure variable important features (discussed later in this section).

For addressing regression problems in regression tree model, Classification and Regression Trees (CART) algorithm is notably used by minimizing the mean squared error (MSE) or mean absolute error (MAE) (15–18). Given the input data, a regression tree using CART is trained with two parts: one is for local fitting, the other is for global fitting. The local model is required to find the independent variable that is the best at partitioning the observations by minimizing local errors (i.e., the sum of squared errors). The global model determines what hierarchical structure

the tree has by aggregating local models and then by minimizing the overall prediction errors.

In statistics, the MSE is also known as the variance, which is the average (expectation) of the squared deviation from the mean. Thus, the generation of a regression tree can be also considered as the minimization of variance (i.e., impurity). The variance of regression tree model (T) can be expressed as below:

$$V(T) = \frac{SSE}{N} = \frac{1}{N} \sum_{c \in \text{leaves}(T)} \sum_{i \in c} (y_i - m_c)^2, \quad m_c = \frac{1}{n_c} \sum_{i \in c} y_i$$

where n is the total number of observations, y_i is the actual target value for i^{th} observation, and m_c is the predicted value for the sample mean response in leaf (i.e., partition) c .

Once the tree has been estimated, we can identify the significant attributes used for predicting the values of a dependent variable. We compare variables that contribute to the tree generation (e.g., minimizing overall errors) by assessing the importance of the independent variables to the dependent variable is by measuring the reduction in variance, which we refer to as the “variable importance (VI)” (4,15,19,20). As we apply the MSE criteria to generate the tree, the reduction in the SSR (i.e., SSE) is aggregated for each independent variable in the estimation process. The change of SSR between the variables indicates the VI for x_j at a certain node, and it can be measured as follows:

$$VI_d(x_j) = \Delta_d = SSR_d - \sum_i SSR_i^d$$

where d represents a node, i is the child of node d , SSR_d is a terminal node of node d (leaf node), and SSR_i^d is an internal node (i.e., the split). For the entire tree, the variable importance score for each variable is calculated as the mean importance over all nodes in a tree (18,19). It can be expressed as follows where D is the total number of nodes:

$$VI(x_j) = \frac{\sum_{d=1}^D VI_d(x_j)}{n\_nodes}$$

In general, the variable importance scores are applied to the standardized metric values (ranging from 0 to 1), but we compare relative importance between independent variables by using percent values. For instance, if the variable has the highest importance, “contribution,” the variable importance score becomes 100 percent.

3. Data

This study uses the Residential Energy Consumption Survey Data (RECS) from the U.S. Energy Information Administration (EIA). This microdata is released approximately every five years, and the latest release, from 2009, contains 12083

observations (i.e., rows, households) and 9234 for single family homes and 2849 for multi-family homes, which came from the entire regions in the United States. Specifically, each observation contains ambient information from the survey questionnaire and climate data. The information, for instance, includes households' demographic characteristics (e.g., household size, income, ages of household members, education), building features (e.g., year of built, material, number of floors), energy consumption behavior (e.g., characteristics of electronic appliance and its usage patterns), and climate characteristics (e.g., cooling degree days, climate condition) (see Table 1).

Table 1: Description of data

Variable name	Description
TOTALBTU	Total usage (thousand BTU), 2009
TYPEHUQ	Type of homes (single, multi-family)
HDD30YR	HDD (30 years average)
Climate_Region_pub	Building America Climate Region
UR	Urban or rural by Census
YEARMADERANGE	Year housing unit was built
NUMFLRS	Number of floors in a 5+ unit APT
USENG	Availability of Natural Gas in HVAC
WINDOWS	Number of windows
AVGAGE	Average age of HH. Members
EDUCATION	Education level of HH owner
NHSLDMEM	Household size
MONEYPY	Household income
TOTHSQFT	Total square footage

We use the logarithm of annual total energy consumptions as we have observed that the total consumptions follow an approximately log-normal distribution (see Fig. 1). Non-parametric models (e.g., machine learning) are likely to have better estimation with the values in the log-transformed normal distribution (8,21,22). In addition, residential energy consumptions are significantly varied by the type of home, our study, therefore, classify all households into two types: single-family and multi-family.

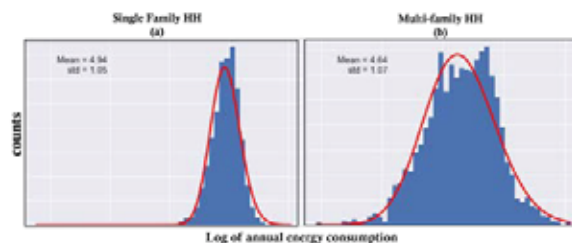


Fig 1: Lognormality of building energy consumption, (a) distribution for single family and (b) distribution for multi-family

All the models estimated in our study are evaluated through cross-validation process (21,23), which

prevent overfitting issues in model accuracy. Specifically, we use stratified K-fold cross-validation method, and it generally performs better in data that contains numerous categorical variables. For instance, RECS data can be categorized by different classes such as house type and climate conditions, and such classes are required to be well-balanced while estimating the models. In general, stratified K-fold cross-validation method performs relatively better in addressing these class imbalance issues (8,21).

4. Results and discussions

Our analysis mainly answers the question of which factors are required to be considered as important when it comes to residential energy demand. Specifically, Fig 2 shows the determinants of residential energy consumption estimated by a regression tree method with the RECS data. Specifically, relative variable importance (RVI) is used for the single and multi-family homes.

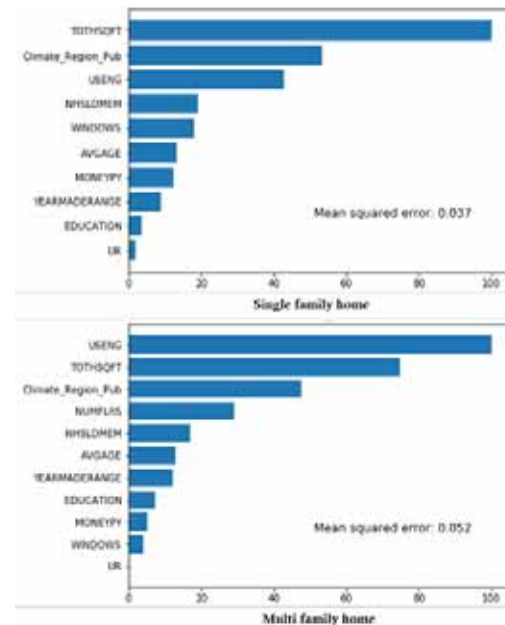


Fig 2 Relative variable importance by the type of household (single family and multi-family home)

For the single-family case, total square footage of a residential building is almost 2 times important as the next important variable (i.e., climate condition), and income and vintage of the building are relatively not as important as other variables. The multi-family case, on the other hand, the availability of natural gas for HVAC is the most crucial variables, and the level of importance for other variable is similar to the that of the single-family case. Specifically, this difference is linked to the fact that multi-family homes are prone to be more sensitive to the availability of natural gas in the building because their HVAC is mostly operated by central systems. These findings are consistent with the results from the previous studies

Based on the significant findings from the previous result (Fig 2), we segment the data into two main different climate conditions such as “hot” and “cold”, which are classified by AIA climate zone which is created by Office of Energy Efficiency and Renewable Energy (24). This classification enables us to control regional variations in climate condition within the model and investigate the impact of other variables under the same climate and residential settings. Specifically, our study creates 4 different model configurations (i.e., cold regions for single and multi-family and hot regions for single and multi-family) to identify the drivers of residential energy consumption while controlling climate impacts. Fig 3 presents the relative variable importance of cold and hot climate conditions for single-family cases. The result shows that variable important differs significantly between the two climate conditions. Specifically, household income has significant impacts on energy consumption for single-family household in cold climate conditions than in hot climate conditions.

Fig 4 presents the results of cold and hot climate conditions for multi-family homes. Specifically, for the cold climate regions, the availability of natural gas is almost 3.5 times important as the total square footage, while total square footage is the most important variable in other cases. In addition, in multi-family cases, household income has relatively lower impacts on the residential energy consumption than in single-family cases.

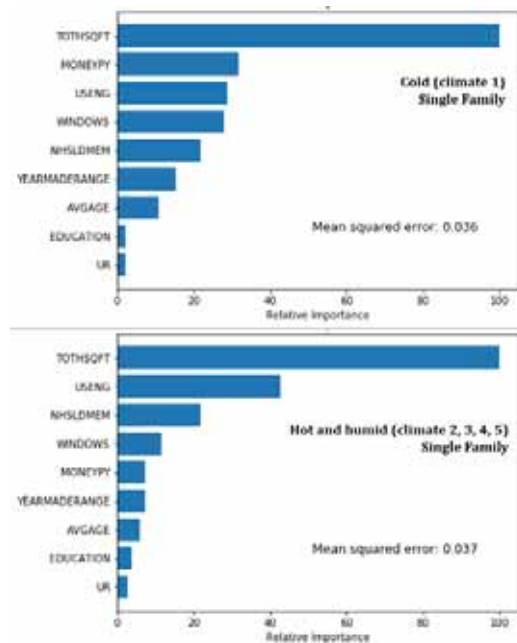


Fig 3: Relative variable importance based on AIA climate conditions (single family homes)

5. Conclusions and outlook

Our study uses a regression tree method to investigate residential building energy consumption

profiles based on the RECS dataset. Specifically, the models aim to identify the drivers of residential energy consumption while segmenting the whole dataset into two main categories: climate conditions and the type of homes. As for enhancing the applicability of models, we purposely use limited information that is accessible to the public data sources. Although using more variables (e.g., physical building information and detailed household energy consumption patterns) is likely to give better modeling accuracy, it will decrease the usefulness of the models due to the lack of such detailed data. In addition, to ensure statistically confident estimating, we apply the stratified K-fold cross-validation. Our models for identifying the drivers of residential energy consumption perform acceptably well.

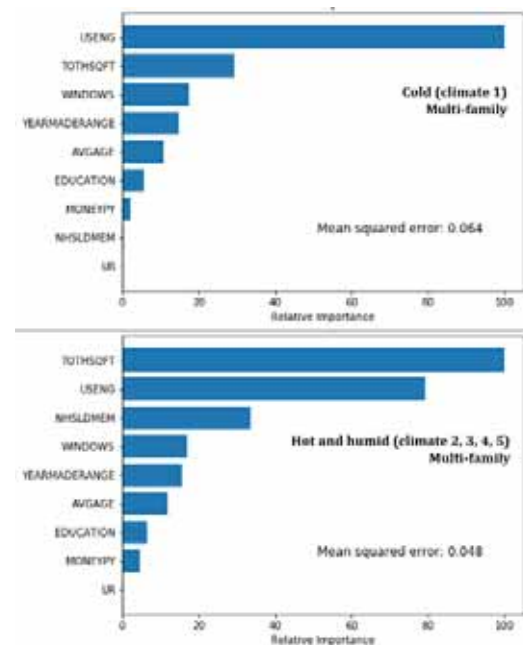


Fig 4: Relative variable importance based on AIA Climate zones (Multi-family homes)

For the models based on different home types, the results from the RVI indicate that important factors (i.e., variables) affecting the energy consumption are total square footage, climate conditions, and the availability of natural gas related to HVAC. Furthermore, we control climate impacts and home types. Most of the results are consistent with the previous models (Fig 2), household income, however, becomes as important as the availability of natural gas for single family homes in cold climate condition.

This study contributes to the literature by not only providing useful information with accessible information but also suggesting effective and cost-efficient modeling approaches. Furthermore, the findings from this study can be used for initial information about energy consumption profiles as well as guidelines for data collection works. For future

work, the model validation process can be conducted by applying our models to other cities or communities. After the validation, we may geographically relate urban forms and residential energy consumption and enhance the capability of the model by using more public accessible data.

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Evaluation of Moisture Indices for Management of Insulated Walls in Canada

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Abstract:

This study reviews several moisture indices used in assessing the performance of moisture management for insulated walls in Canada. The Moisture Index (MI), was reviewed and critiqued because of its current role in the building code for characterizing climate across Canada. Alternative moisture indices based on different factors like precipitation, temperature, dominant wind direction, relative humidity, etc, were statistically evaluated as possible alternatives to the MI. A sensitivity analysis was conducted to compare variability in each index in order to compare and to show limitations of each for several different cities spanning different climatic regions in Canada. Results showed that when certain indices were much more sensitive to changing temperature, others were more sensitive to changing relative humidity or rain intensity. Finally, a comparative study was done to compare the values of different indices for individual cities, and to compare different cities when examining individual indices. In this comparative study, a new method that uses a hypothetical city as a basis of comparison, (BOC_{city}) as normalizing factor was employed to provide insight into the relative performance of these indices. This method proved that some indices are much better at displaying the variability across the country, while others have little variability.

Keywords:

moisture management, climate indices, insulated wall performance

1. Introduction

High moisture content in building envelopes can adversely affect building performance and in extreme cases lead to building failures. Mold formation and freeze thaw damage are both moisture related problems in building envelopes. Mold and mildew can adversely affect the building environment and pose a serious health issue for the inhabitants. Freeze-thaw damage on the other hand could significantly affect the appearance of the façade and result in decreased energy performance and lifetime of the building envelope. Thus, moisture performance in building envelopes needs to be critically evaluated to facilitate proper and long-lasting design.

Moisture indices are a standard tool used in the industry to assess hygrothermal performance (moisture management) and susceptibility to mold growth, freeze-thaw damage, and other environmental exposure leading to degradation in the building envelope. Moisture indices are a measure of one or more environmental parameters like relative humidity (RH) and temperature, that impact hygrothermal response. The aim of this paper is to review the efficiency of moisture indices used in the moisture management of insulated walls in Canadian cities. The paper begins by reviewing the role of a standard index called the Moisture Index (MI) in characterizing different climate regions for moisture management of buildings. It provides insight into both advantages and disadvantages of using MI as a building code. Then, alternative moisture indices (applicable to building performance) are discussed and statistically evaluated.

The methodology for this evaluation involved two approaches: a *sensitivity analysis* to understand the variability in each index. This was conducted to compare and show limitations of each when applied to several different cities in Canada with drastically different climatic regimes. The second approach was a *comparative study* that compared all the indices together for each of the selected cities in order to show how much variation there is given the variation in the climate across Canada.

2. Climate indices for building applications

To begin examining moisture index values across Canada, the different climatic regimes across the country needs to be categorized. One basis of grouping climate schemes is to divide them genetically and empirically. Genetic classification is concerned with the origin, i.e. climates are grouped into factors that are causing them, e.g. air masses, wind zones, etc. Empirical classification is based on essential elements like observation and experience [1]. There are traditional climate classifications that are more biased towards agriculture and human habitability, but consequently are less useful and not refined enough for identifying acceptable building codes. Thus, indices using traditional climate classifications like the modified version of Koppen by Trewartha [2] are not examined in this work.

2.1 Moisture Index (MI)

This moisture index method was used to characterize climate with respect to risk of moisture related building

envelope problems and to select locations of interest for serving as input for simulation purposes. The concept of classifying locations based on a moisture index was suggested in the Task 4 report of MEWS consortium [3]. In MEWS consortium, two independent climate indices, wetting index (WI) and drying index (DI) were developed to characterize the climates of the cities. Both the indices are independent of each other. WI describes the wetness of a climate (potential for a wall to get wet) and DI describes dryness of the climate (potential for a wall to dry out after getting wet). In its general form, Moisture Index is a function formed from combining WI and DI. The wetting component can be defined as a function of annual rainfall, annual directional rainfall, driving-rain index ($\text{m}^2/\text{s-year}$), average annual rain load on a wall or rainfall on the ground ($\text{kg}/\text{m}^2 - \text{year}$).

Ideally, the wetting component should measure the amount of water that a wall must manage by deflecting, draining or drying. But for the sake of simplicity, the Wetting Index (WI) was defined as the average annual rainfall. The Drying Index (DI) is the difference between the humidity ratio (also known as the mixing ratio) at saturation and the humidity ratio of the ambient air. The humidity ratio of the ambient air (w_{out}) is the amount of water vapour that air can hold at outside temperature. Humidity ratio at saturation ($w_{\text{saturation}}$) is the theoretical maximum amount of water vapour that air can hold at that same temperature. Drying Index (hourly) can be calculated using Equation (1):

$$\Delta w(t) = w_{\text{sat}}(t) - w_{\text{out}}(t) \text{ kg water/kg air} \quad (1a)$$

$$w = 0.622 * (v_p / (p - v_p)) \text{ kg water/kg air} \quad (1b)$$

where t = hourly temperature; v_p = vapour pressure in kPa; and p = total mixture pressure (assumed to be 101.1 kPa). More succinctly Δw is:

$$\Delta w = w_{\text{sat}} * (1 - \mu) \text{ kg water/kg air} \quad (1c)$$

where w_{sat} = humidity ratio at saturation; μ = degree of saturation; and $\mu = w_{\text{out}}/w_{\text{sat}}$.

For calculating an annual value of DI using hourly values, the following equation can be used

$$DI = \left(\frac{1}{n}\right) \sum_{i=1}^n \sum_{h=1}^k \Delta w(h) \text{ kg water/kg air} \quad (2)$$

where DI is the Drying Index in kg water/kg air-year; n is the number of years under consideration; and k is the number of hours in a particular year, i.e. either 8760 or 8784 hours. DI can be calculated using long term climatic normals (Equation 3) by taking average annual temperature and average annual relative humidity.

$$DI = \Delta w * k \text{ kg water/kg air} \quad (3)$$

Using average annual temperature leads to an underestimation of DI. As a counter measure, equivalent average temperature, T_{eq} is used.

$$\begin{aligned} T_{\text{eq}} &= T + T_{\text{correct}} \\ T_{\text{correct}} &= 0.2206 * AR - 0.9073 \end{aligned} \quad (4)$$

where: T is annual average temperature from the climate normal; T_{correct} is the correction factor; and AR is the annual range.

Finally, the MI is defined as the ratio of WI to the DI. The higher the MI value, the higher the risk for moisture related risk to the building envelope at that location. The Equation for the MI is shown below [4].

$$MI = WI/DI \quad (5)$$

For comparing MI of a given set of locations, each MI value is normalized by dividing with highest MI value in the set. However, in MEWS consortium [3] MI was calculated using a different approach. Both WI and DI were normalized separately using Equation 6 and then MI was calculated using Equation 7.

$$I_{\text{normalized}} = (I - I_{\text{min}})/(I_{\text{max}} - I_{\text{min}}) \quad (6)$$

$$MI_{\text{MEWS}} = \sqrt{WI_{\text{normalized}}^2 + (1 - DI_{\text{normalized}})^2} \quad (7)$$

Thus, obtained MI values were used to rank different cities, the city with the highest MI being ranked at the top and so on. Different rankings for the same city can result when using both MI types (MI and MI_{MEWS}). Two important assumptions in this analysis are: (i) wall response to environmental conditions was not considered as part of the climate analysis; and (ii) Wetting Index and Drying Index were given equal weight.

2.2 RHT Index

Increased RH level with varying temperature loads can lead to varying degrees of damage to the building envelope and significantly affect the performance and lifetime of a building. NRC Canada set up a task force specifically for evaluating the Moisture Management for Exterior Wall Systems (MEWS), in which they studied moisture performance of stucco clad wall, EIFS wall, masonry wall and wood frame wall [4]. They developed a novel concept being the RHT index wherein they computed an RHT number by taking the summation of the product of the RH and Temperature inside the wall for the given time period and evaluated the moisture risks, based on the RHT index. Important thing to note here is that the RHT index developed by MEWS takes into account RH and T inside the wall but in this analysis same equation is used for outside RH and T taken from the weather data. Equation 8 gives the mathematical representation of the RHT index as defined in MEWS consortium Task 8 report [4].

$$\text{Cumulative RHT} = \sum (RH - RH_x)(T - T_x) \quad (8)$$

If the $RH \leq RH_x\%$ and $T \leq T_x$, the RHT value for that time stamp is zero. Two RHT indices of RHT (80-5) and RHT (80-0) were used to evaluate the moisture performance of the stucco wall used for the analysis. Although the RH and temperature limit defined in the MEWS report was RHT (95-5), lower limits of RHT (80-5) and RHT (80-0) were used to assess if there is moisture risk at lower values.

2.3 Driving-Rain Index and Derivations

The driving-rain index is simply the sum of the product of wind speed and rainfall and represents roughly the amount of water passing through a vertical plan or deposited on a wall. There are two types of driving-rain index, the annual Driving-Rain Index (aDRI) and the directional Driving-Rain Index (dDRI).

2.3.1 Annual Driving-Rain Index (aDRI)

aDRI is simply the sum of the product of horizontal rain intensity and wind speed over the year. It can be calculated using Equation 9 [3].

$$\sum_{t=1}^n U_{10} * R_h / 1000 \text{ m}^2/\text{sec-year} \quad (9)$$

where: U_{10} is hourly wind speed at 10 m; R_h is horizontal rainfall (mm/m²-h); and n is the number of hours in a year, i.e. either 8760 or 8784 hours. If annual average data are used instead of hourly rainfall and wind data, an underestimation of up to 40% was reported [5][10]. This is a simple approach since it uses only two elements, wind speed and rainfall, which are readily available. The aDRI does not have a directional component and it does not give a measure of the potential for "drying out."

2.3.2 Directional Driving-Rain Index (dDRI)

The dDRI is similar to aDRI except that direction factor is included in the product terms. The dDRI can be different for two locations that have same aDRI. For example, if one location has most of the wind-driven rain in one direction, a single wall will take most of the rain load. Other locations may have received an average rain load divided in four directions and individual wall will receive only a quarter of the rain load perhaps. The dDRI can be calculated using equation 10 as given in the UK method [6]

$$dDRI = U * \cos(\theta) * r_h \quad (10)$$

where: U is the wind speed at 10 m (m/sec); r_h is the horizontal rain intensity (mm/m²-h); and θ is the angle of the wind to the wall normal. Apart from advantages of aDRI, dDRI also provides a clear indication of the distribution of rain loads with respect to direction and reflects the loads to which the most exposed wall of a building will be subject. But there is no measure of drying out potential and more calculations are required as compared to aDRI due to the addition of third element, wind direction.

2.3.3 Derivatives of the dDRI

There are different methods available for estimating the rain load passing through a vertical surface (or the amount of water impinging on a wall by using climatic data. Most of these methods are derivatives of the Directional Driving-Rain approach. John Straube's method [7], a derivative of Lacy's original approach [8], includes effects of wind speed and direction, rainfall intensity, raindrop size and aerodynamic effects on the amount of water deposited on a vertical surface.

The method recommended by Straube was in fact used in MEWS Task 4 [3] for determining predominate rainfall directions and reference years. The annual expected load on a vertical surface can be calculated by using hourly wind speed, wind direction and rainfall intensity. The predominant direction is defined as the cardinal orientation that produces the greatest rain load on the wall. The height of the wind speed measurements was assumed to 10 m. The top corner of the building was the assumed to be the location of interest; this was used in determining the RAF factor.

$$WDR = RAF * DRF(r_h) * \cos(\theta) * V(h) * r_h \quad (11)$$

where: WDR is the wind driven load (l/m²-h); RAF is the rain admittance factor; r_h is the horizontal rainfall intensity (mm/m²-h); $V(h)$ is the wind speed at the height of interest (m/sec); and θ is the angle of the wind to the wall normal. Apart from having the same advantages as dDRI, this approach has an advantage in detailed modeling of specific buildings since elements like aerodynamics effects, terrain, topography, obstructions (other buildings) and wall locations (e.g. top corner) can be considered. However, many more calculations and factors are required in calculating WDR.

2.4 Temperature and Rainfall

Temperature and moisture are two key factors that affect durability of buildings and can be used to classify climates.

2.4.1 Rain and Heating Degree Days

Degree days are simplified representations of outside air-temperature data. Cooling degree-days (CDD) for a given day are the number of degrees Celsius that the mean temperature is above 18 °C. If the temperature is equal to or less than 18 °C, then the number will be zero. For example, a day with a mean temperature of 20.5 °C has 2.5 cooling degree-days; a day with a mean temperature of 15.5 °C has zero cooling degree-days. Heating Degree-days (HDD) for a given day are the number of degrees Celsius that the mean temperature is below 18 °C. If the temperature is equal to or greater than 18 °C, then the number will be zero. For example, a day with a mean temperature of 15.5 °C has 2.5 heating degree-days; a day with a

mean temperature of 20.5 °C has zero heating degree-days.

According to Cornick [2001] a country may be divided into two zones based on a single lower limit on rainfall and a single upper limit on the number of heating degree-days. In Canada, Zone 2 is a region having annual rainfall of greater than 1100 mm and minimum of 5000 heating degree-days. All other regions fall under Zone 1 [1]. Thus, the entire nation of Canada is divided into only two zones. Cities like Calgary, Toronto and Iqaluit are combined into a single zone although their climates vary drastically. Similarly, but providing better contrast, Lstiburek produced similar zonings based on rainfall and temperatures. The North American map was divided into five different climate zones based on heating degree-days below 65 °F (18°C), average monthly temperature and precipitation [9].

These approaches use simple definitions of climate regions and use climate data that are easily available. However, these approaches do not address the issue of water loading on walls, nor is there any acknowledgment of drying periods. All of the approaches define immediate limits to climate zones rather than providing information that would characterize the climates of various locations. That information can help other researchers to decide where the boundaries to climate zones should be drawn.

2.5 Wetting and Drying

Moisture Index approach which is based on wetting and drying potential was discussed in section 2.1. Thirteen Canadian cities were ranked using the Drying Index, Wetting Index and their combination, Moisture Index (WI/DI and MEWS).

Wetting index (WI) was calculated using two different methods and ranked accordingly. The first method uses annual rainfall and the second one uses annual rain load (Straube's method) as explained in section 2.3.

MI was calculated using DI and both possible WI, giving us two different rankings for MI. A different ranking is obtained when MI is calculated using WI calculated from annual rain load rather than annual rainfall data. This ranking can be considered more realistic since it reflects the actual environment for the wall. It should be noted that there is still lack of experimentally observed data to correlate various levels of moisture index to specific risks of premature deterioration. There is no basis to support the relative weighting of the WI and DI (assumed to be 1:1)¹.

¹ Wetting permeates deeply into the building, whereas drying occurs primarily at the surface, consequently the wetting index should be weighted more highly than the drying index, rather than

2.5.1 MEWS approach

Since the MEWS approach used a different method of calculating MI (as discussed earlier), a different ranking was obtained. Since annual rainfall data is readily available, developing wetting indices using this data is more practical. Normalization helps to set quantifiable limits on the MI_{MEWS} which can be used for developing different climate zones. However, there is no evidence to support weighting of the wetting index to drying index. Also, without considering orientation, no insight is provided on severity of wetting the walls.

3. Methodology

3.1 Sensitivity Analysis

Sensitivity analysis is a technique used to determine the impact of changes in independent variables upon a particular dependent variable. Since each index is a function of common variables like temperature, relative humidity, wind speed, etc.; analysis was done to see how much change in input variables leads to changes in output variables.

Basis of comparison (BOC) values were kept constant for every index analyzed, for e.g. Temperature (T) was considered 20°C as a base for every index. Each input variable was changed by certain increments (say 5%) in each direction, i.e. +5%, +10%, +15%, +20%, +25% and -5%, -10%, -15%, -20%, etc up to maybe 50% - depending upon the variable. Then the index was calculated each time for each change in the input variable. Finally, for the purpose of presentation, the values of the sensitivity analysis were divided by the BOC value, so that the BOC value should be 1. This normalizing scheme allows us to show the sensitivity of all input variables on the same graph. Table 1 shows a calculation sheet for annual Driving Rain Index (aDRI) which is a function of two variables, Wind Speed and Horizontal Rain Intensity. In this case, BOC values for wind speed and rain intensity are 4 (m/s) and 5 (mm/m²-hr), respectively.

3.2 Comparative Study

The comparative study was divided in two parts. The first one was to compare different indices for individual cities and second one was the reverse, i.e. compare different cities using individual indices. In order to compare different indices all together, a normalization technique was adopted. In this technique, a hypothetical city, named as BOC_{city}, was chosen as a reference point. Next step was to decide climate normals for BOC_{city}. Long term climate normal (1981 – 2010) of all the 13 Canadian cities under study were collected and the mean average of each variable

equally as at present. As a result of these three factors, design solutions to manage moisture may be advised in a wider region than necessary. Appendix D (Forentik Canada Corporation dissenting comments)

(Temperature, RH, annual rainfall, etc.) was

Changing Wind Speed (m/sec)					Changing Horizontal Rain Intensity (mm/m ² -hr)				
% change	Horizontal Rain Intensity	Wind Speed	aDRI	aDRI/BOC	% change	Horizontal Rain Intensity	Wind Speed	aDRI	aDRI/BOC
-50	5	2	10	0.5	-25	3.75	4	15	0.75
-45	5	2.2	11	0.55	-22.5	3.875	4	15.5	0.775
-40	5	2.4	12	0.6	-20	4	4	16	0.8
-35	5	2.6	13	0.65	-17.5	4.125	4	16.5	0.825
-30	5	2.8	14	0.7	-15	4.25	4	17	0.85
-25	5	3	15	0.75	-12.5	4.375	4	17.5	0.875
-20	5	3.2	16	0.8	-10	4.5	4	18	0.9
-15	5	3.4	17	0.85	-7.5	4.625	4	18.5	0.925
-10	5	3.6	18	0.9	-5	4.75	4	19	0.95
-5	5	3.8	19	0.95	-2.5	4.875	4	19.5	0.975
0	5	4	20	1	0	5	4	20	1
5	5	4.2	21	1.05	2.5	5.125	4	20.5	1.025
10	5	4.4	22	1.1	5	5.25	4	21	1.05
15	5	4.6	23	1.15	7.5	5.375	4	21.5	1.075
20	5	4.8	24	1.2	10	5.5	4	22	1.1
25	5	5	25	1.25	12.5	5.625	4	22.5	1.125
30	5	5.2	26	1.3	15	5.75	4	23	1.15
35	5	5.4	27	1.35	17.5	5.875	4	23.5	1.175
40	5	5.6	28	1.4	20	6	4	24	1.2
45	5	5.8	29	1.45	22.5	6.125	4	24.5	1.225
50	5	6	30	1.5	25	6.25	4	25	1.25

considered as the climatic normal of BOC_{city} for the 1981-2010 period.

Table 1 Sensitivity analysis of aDRI.

Table 2 Climatic normals for various cities.

For e.g. average annual temperature (using long term climatic normals) were recorded for different cities and the mean of these values was considered as the annual average temperature for BOC_{city}. Wind direction predominance was not considered for BOC_{city}. The indices under consideration (aDRI, dDRI, DI, WI, etc.) were calculated for BOC_{city}. Table 2 shows a part of the excel spreadsheet for calculating climatic normals for BOC_{city}.

Finally, different indices were normalized using respective BOC_{city} indices. For e.g. the normalized aDRI value for Victoria was obtained by dividing aDRI_{Victoria} by aDRI_{BOCcity} and so on for all the indices for each city. Table 3 shows part of the spreadsheet for calculating normalized values of different indices for Canadian cities studied in this work. One important thing to note here is that DI and WI were not normalized using MEWS normalization. They were simply calculated by dividing by DI_{BOCcity} and WI_{BOCcity}, respectively.

4. Results and Discussions

4.1 Sensitivity Analysis

Figure 1 (a-g) shows graphs of the sensitivity of aDRI, dDRI, RHT, WDR, DI, MI and MI_{MEWS}.

aDRI is equally sensitive to changes in input variables, wind speed and rain intensity; dDRI is much more sensitive to changing wind speed and rain intensity as compared to the changing wind direction. RHT is more sensitive to changing relative humidity as compared to changing temperature. WDR is highly sensitive to the RAF, and equally sensitive to wind speed, rain intensity and DRF. Sensitivity to wind direction is similar to that of dDRI. It can be seen that with initial increases in temperature, DI rises steadily up to a certain extent and

then a steep exponential rise is seen. Since the degree of saturation (μ) is ratio of w_{out}/w_{sat} , it is inversely proportional to w_{sat} . DI decreases linearly as the value of μ is increased.

MI increases or decreases linearly as WI is increased or decreased. On the other hand, since MI is inversely proportional to DI, it decreases as DI increases. MEWS MI is equally sensitive to both DI_{normalized} and WI_{normalized}. MI increases as WI is increased and decreases as WI is decreased, whereas for DI, vice-versa is true.

4.2 Comparative study

4.2.1 Comparison between indices for individual cities

Since different indices have different units of measurement, a common normalizing scheme was adopted. In this comparison, the hypothetical city, BOC_{city}, was considered as a reference point for all other cities. The indices under consideration were calculated for BOC_{city} by keeping input variables constant for all the indices, similar to what was done in the sensitivity analysis. The results show that Victoria's highest normalized index is Moisture Index (annual rainfall) having a value of 1.24, closely followed by annual Driving Rain Index at 1.14; whereas the lowest normalized index is dDRI with value of 0.73. Figure 2 shows comparison of various normalized indices of Victoria, BC.

Table 4 shows the mean, range, standard deviation, highest value, lowest value and coefficient of variation of normalized index for thirteen Canadian cities under consideration. Vancouver showed a similar trend as Victoria. Both of the west coast cities showed consistency with high rainfall and low drying index. Its lowest normalized index is the Drying Index at 0.83, whereas the highest ranked index is the Moisture Index (Straube's) at 1.94. Victoria's coefficient of variation (CV) is 16.06, the lowest among the cities being

Climatic Normals	BOC _{city}	Victoria	Vancouver	Edmonton	Calgary	Winnipeg
Temperature (°C)	5.38	10	10.4	2.6	4.4	3
Standard deviation (°C)	1.34	0.5	0.6	1.1	1	1.2
Annual Rainfall (mm)	742.55	845.3	1152.8	338.8	326.4	418.9
RH - 0600LST %		86.6	85.9	79.3	71.7	82.4
RH - 1500LST %		65.8	70.3	56.3	48.3	61.1
Av. RH %	72.24	76.2	78.1	67.8	60	71.75
Av. Vapour pressure (kPa)	0.82	1	1	0.6	0.6	0.8
Wind Speed (km/h)	14.41	9.1	12.2	12.2	14.2	17.1
Wind Speed (m/sec)	4.01	2.53	3.39	3.39	3.95	4.75
Frequent direction		W	E	S	S	S
Annual Range	26.56	12.8	14.4	30.2	26	38.1

compared. Vancouver's coefficient of variation is 20.75, which is the second lowest.

Edmonton's highest value normalized index is directional driving rain Index at 1.09, which was closely followed by the Drying Index at 1.03. Less rainfall was depicted by lower ranked normalized indices of Wetting Index (Straube's), Moisture Index (Straube's) and Moisture Index MEWS (Straube's) with values of 0.42, 0.41 and 0.42, respectively. Its coefficient of variation is 44.24. Calgary has the highest normalized Drying Index of 1.38 and the lowest normalized Moisture Index (annual rainfall) of 0.28. It ranks highest in coefficient of variation with a value of 57.37. Similarly, a climate trend of 'Prairies' can be clearly seen from the graphs of Edmonton, Calgary and Winnipeg (not shown). Winnipeg shows similar results as Calgary, with a Drying Index ranking at the top with 1.16 and the lowest ranked index being the Moisture Index (Straube's) with a value of 0.33. Its coefficient of variation is 48.84.

Windsor's coefficient of variation is 33.35, normalized annual Driving-Rain Index is ranked highest at 1.45 while normalized Moisture Index (Straube's/Rain load) is ranked the lowest at 0.54. In contrast to Windsor, Toronto showed an interesting trend in ranking of the normalized indices. Drying Index came out at the top of the other indices with a value of 1.13, however directional Driving-Rain index and Moisture Index (Straube's) both (data not shown) ranked the lowest for Toronto with a normalized index value of 0.33. Its coefficient of variation is 46.27. Ottawa showed a fairly similar trend when compared to Toronto with the Drying Index ranking the highest at 1.20, directional Driving-Rain index ranking the lowest at 0.4. Ottawa's coefficient of variation is 37.20.

Comparison of normalized indices for the City of Montreal shows very interesting results with normalized annual Driving-Rain Index having the highest value of 1.25, while normalized directional Driving-Rain Index has the lowest value of 0.44. Its coefficient of variation is 37.52, very close to Ottawa.

Table 3 Normalization of indices for various cities.

Climate Index	BOCcity	Victoria BC	Vancouver BC	Edmonton AB	Calgary AB	Winnipeg MB
aDRI (m ² /sec/year)	2.97	3.4	4.8	1.9	1.8	2.4
Normalized aDRI	1	1.1448	1.6161	0.6397	0.6060	0.8080
dDRI (m ² /sec/year)	2.75	2.0	3.6	3.0	1.1	1.0
Normalized dDRI	1.0	0.7	1.3	1.1	0.4	0.4
WDR (Straube's) (l/m ² /year)	495.17	443	803	207	252	187
Normalized Straube's	1	0.8946	1.6217	0.4180	0.5089	0.3776
DI(kg water/kg air/year)	19.19	17	16	19.75	26.5	22.25
Normalized DI	1.0000	0.8859	0.8338	1.0292	1.3809	1.1595
WI (annual) (l/m ² /year)	742.55	815	1055	360	290	390
Normalized WI annual	1.0000	1.0976	1.4208	0.4848	0.3905	0.5252
WI (Straube's)	495.17	443	803	207	252	187
Normalized WI Straube's	1.0000	0.8946	1.6217	0.4180	0.5089	0.3776
MI Annual	38.6946	47.9412	65.9375	18.2278	10.9434	17.5281
Normalized MI Annual	1.0000	1.2390	1.7040	0.4711	0.2828	0.4530
MI Straube's	25.8035	26.0588	50.1875	10.4810	9.5094	8.4045
Normalized MI Straube's	1.0000	1.0099	1.9450	0.4062	0.3685	0.3257
MI MEWS Annual	1.0000	1.1035	1.4305	0.4857	0.5456	0.5489
MI MEWS Straube's	1.0000	0.9019	1.6302	0.4191	0.6357	0.4099

Table 4 Normalized indices for 13 Canadian cities.

City	Mean	Range	Standard Dev.	Lowest Index and value		Highest Index and value		CV
Victoria	1.00	0.51	0.16	dDRI	0.73	MI Annual	1.24	16.06
Vancouver	1.50	1.11	0.31	DI	0.83	MI Straube's	1.94	20.75
Edmonton	0.60	0.68	0.27	MI Straube's	0.41	dDRI	1.09	44.24
Calgary	0.57	1.10	0.33	MI Annual	0.28	DI	1.38	57.37
Winnipeg	0.55	0.83	0.27	MI Straube's	0.33	DI	1.16	48.84
Windsor	0.93	0.91	0.31	MI Straube's	0.54	aDRI	1.45	33.35
Toronto	0.66	0.80	0.31	dDRI	0.33	DI	1.13	46.27
Ottawa	0.70	0.80	0.26	dDRI	0.40	DI	1.20	37.20
Montreal	0.81	0.81	0.31	dDRI	0.44	aDRI	1.25	37.52
Fredericton	0.82	0.67	0.28	aDRI	0.47	MI MEWS Annual	1.15	34.83
Iqaluit	0.69	1.06	0.39	dDRI	0.25	aDRI	1.31	57.20
Shearwater	1.55	1.67	0.50	DI	0.69	aDRI	2.36	32.14
St Johns	2.21	3.27	0.99	DI	0.55	MI Straube's	3.81	44.71

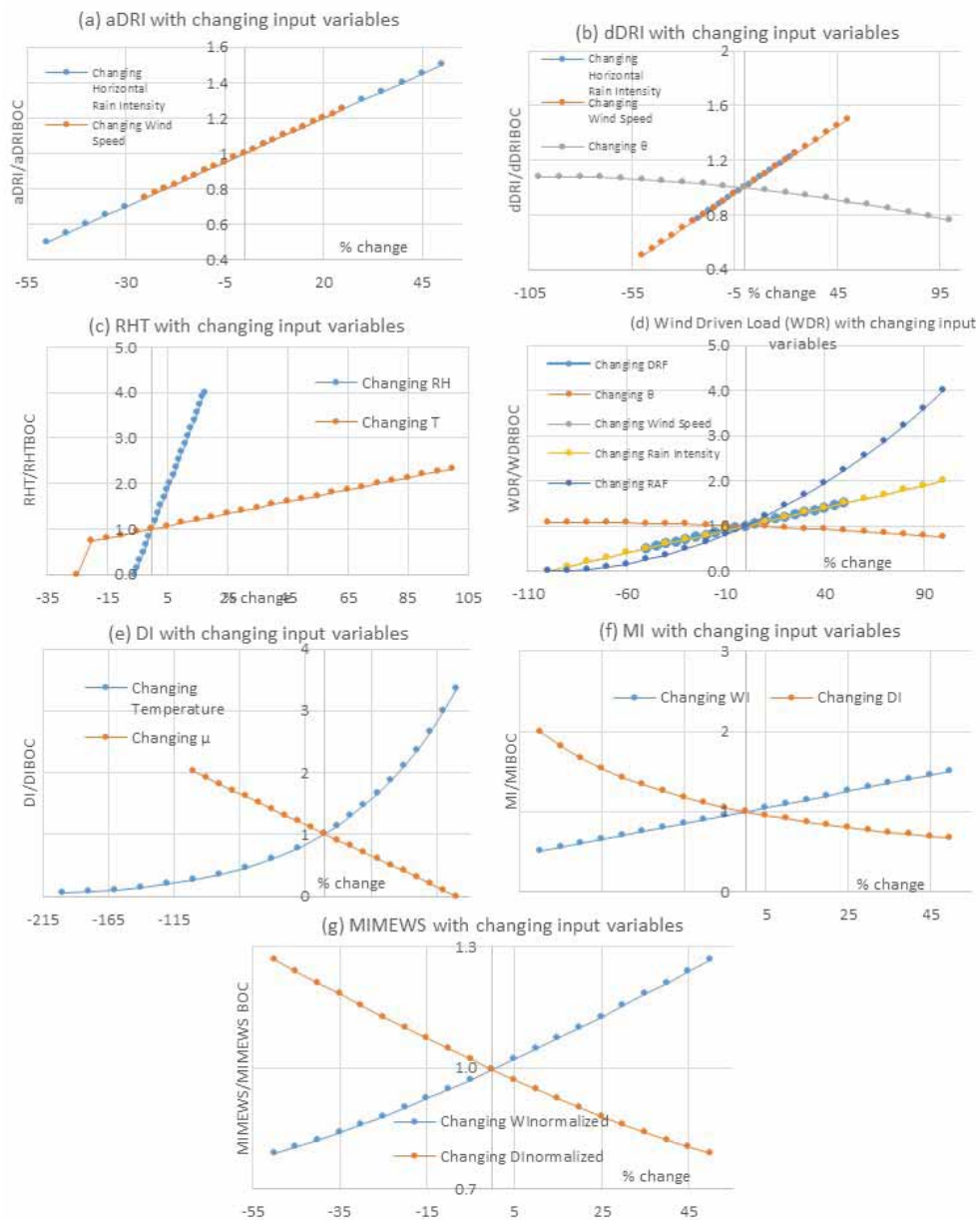


Figure 1(a) – 1(g) Sensitivity analysis of various climate indices.

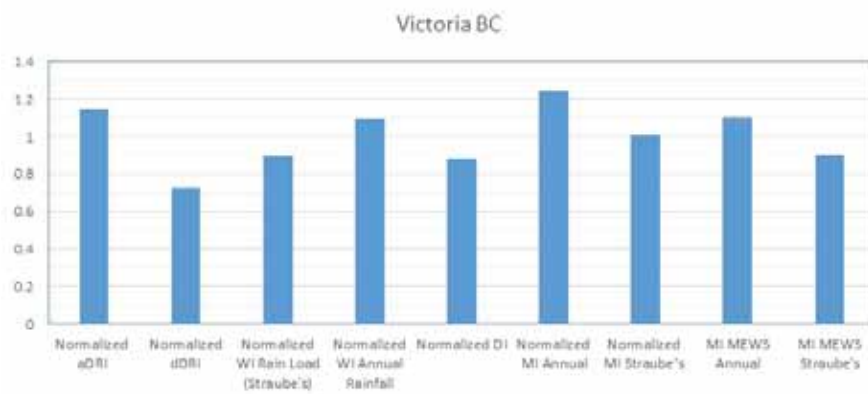


Figure 2 Comparison of normalized indices for Victoria BC

Fredericton's CV is 34.83 and highest normalized index was Moisture Index MEWS (annual rainfall) with a normalized value of 1.14. Normalized annual Driving-Rain Index is Fredericton's lowest index with a normalized value of 0.47. Normalized annual Driving-Rain Index was ranked highest for Iqaluit NU. It has a normalized value of 1.31. The lowest ranked index is directional Driving-Rain Index at 0.25 and second lowest being Drying Index with a normalized value of 0.32. Its coefficient of variation is the second highest with value of 57.20. Shearwater's normalized annual Driving-Rain Index has the highest value of 2.36 while the normalized Drying Index has the lowest value of 0.69. Its coefficient variation is 32.14. St John's normalized Moisture Index (Straube's/Rain load) having the highest value of 3.81 while Drying Index holds the lowest spot at 0.55. This holds true being St John's receives the highest rainfall in the country. It has coefficient of variation of 44.71.

4.2.2 Comparison between different cities for individual indices

Since the normalized index value of each city was calculated in the previous section, the same data was presented for different cities for each normalized index. The obtained values gave rankings of different cities for individual normalized indices. BOC_{city} will always have a reference value of 1 since all other cities were normalized by dividing with the respective index value of BOC_{city} . Figure 3 compares normalized Moisture Index MEWS based on rain load for 13 Canadian cities. Similar trends like MI_{MEWS} (annual rainfall) is shown here with St John's ranking the highest with a normalized index value of 2.13 and Vancouver being second highest with value of 1.63. In contrast, the city of Toronto is ranked the lowest with value of 0.39 and Winnipeg is second lowest with value of 0.41.

Table 5 shows mean, range, standard deviation, highest value, lowest value and coefficient of variation (CV) of the different normalized indices. St John's ranked the highest in aDRI with a normalized value of 3.27, whereas Fredericton has the lowest value of normalized aDRI at 0.47. aDRI has a coefficient of variation of 60.07. Calgary and Edmonton are second and third lowest with normalized index values of 0.61 and 0.64 respectively.

Normalized directional Driving-Rain Index shows coastal cities ranked higher with St John's (1.82) leading among the group, Vancouver and Shearwater ranked second highest with both having normalized value of 1.31 (data not shown). Iqaluit shows the least amount of directional rain with index value of 0.25, while Toronto, Winnipeg and Calgary follow close by with values of 0.33, 0.36 and 0.4 respectively. It has a coefficient of variation of 65.74.

Normalized wetting Index based on annual rainfall shows coastal cities like St John's and Vancouver are ranked higher since they receive more rainfall

throughout the year in contrast with Iqaluit and Calgary which are comparatively dry. St John's normalized index value is 1.61, whereas Iqaluit's normalized index value is 0.35. Normalized wetting index based on rain load (Straube's method) showed similar trend as WI (annual rainfall). Coastal locations like St John's and Vancouver ranked higher with a value of 2.09 and Iqaluit is ranked lowest with a value of 0.33.

Among the rankings of normalized Drying Index, Calgary comes out on top with value of 1.38 while Iqaluit has the lowest value of 0.32. It has the lowest coefficient of variation i.e. 31.44. Normalized Moisture Index based on annual rainfall shows that Calgary has the lowest MI due to a high drying index and low wetting index. St John's clearly comes at the top due to high wetting index and low drying index. Cities like Vancouver, Victoria, Shearwater located on the coasts ranked higher than continental locations like Winnipeg and Edmonton (data not shown).

The normalized Moisture Index based on rain load depicts differences between coastal and continental locations even more distinctly. St John's shows a consistent trend of being highest in moisture index with normalized value of 3.81. However, cities like Fredericton, Montreal and Toronto were now at similar levels as Edmonton and Calgary (data not shown). The lowest value of normalized index is of Winnipeg (0.33) and Toronto (0.33), closely followed by Calgary (0.37). It has the highest coefficient of variation with a value of 99.42. Normalized Moisture Index MEWS based on annual rainfall shows St John's and Vancouver are the highest ranked with respective values of 1.67 and 1.43. Lowest ranked city is Edmonton with a normalized index value of 0.49, closely followed by Calgary (0.55) and Winnipeg (0.55).

5. Conclusions and Outlook

Moisture indices relevant to hygrothermal performance in Canada were reviewed and critiqued. A sensitivity analysis of different moisture indices, i.e. aDRI, dDRI, DI, WI, MI etc. was conducted. It was found that the Drying Index is most sensitive to temperature changes whereas RHT is more sensitive to changes in relative humidity in comparison to changing temperature. Moisture index can be concluded as equally sensitive to drying and wetting, although this will change if equal weights for wetting and drying potential are not used. Indices like aDRI and WDR Straube's method are pretty sensitive to wind direction, although rain intensity plays an important role as well. WDR is most sensitive to change in Rain Admittance Factor (RAF). A hypothetical BOC_{city} was created for a different approach to normalizing various indices under consideration. Using BOC_{city} , a comparative study was conducted to compare all the indices for each city to show how much variation there is in comparison to the variation in climate across these cities. The comparison showed that there was a clear distinction between coastal, prairie and continental locations.

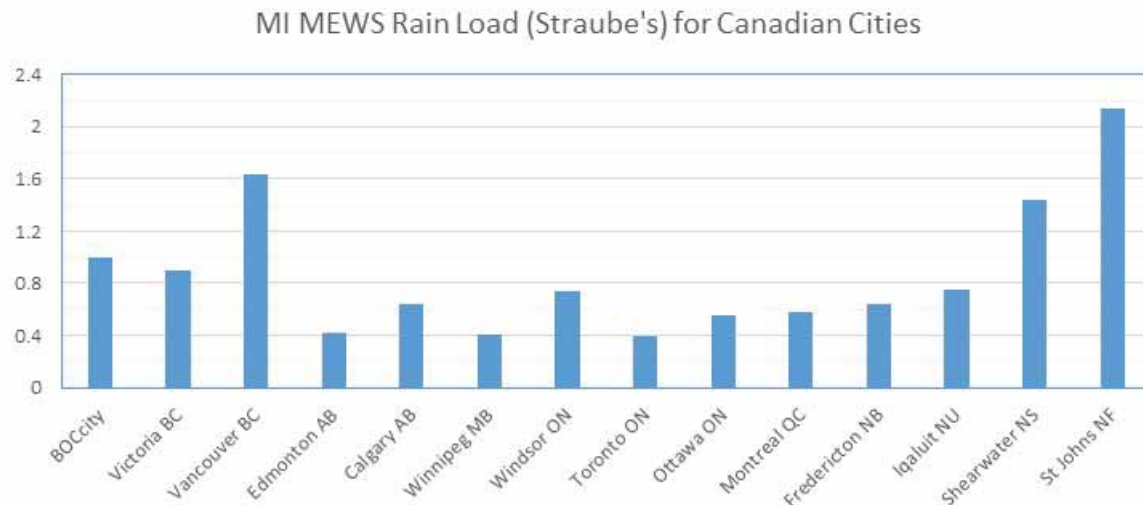


Figure 3 Comparison of different cities (west to east) for Normalized MI MEWS (rain load).

Table 5 Statistics of normalized indices for various cities.

Index	Mean	Range	Standard Dev.	Lowest Ranked City and value		Highest Ranked City and value		CV
Normalized aDRI	1.29	2.79	0.78	Fredericton	0.47	St Johns	3.27	60.07
Normalized dDRI	0.74	1.56	0.49	Iqaluit	0.25	St Johns	1.82	65.74
Normalized WI Annual Rainfall	0.93	1.26	0.41	Iqaluit	0.35	St Johns	1.61	43.81
Normalized WI Rain Load (Straube's)	0.80	1.76	0.56	Iqaluit	0.33	St Johns	2.09	69.30
Normalized DI	0.97	1.06	0.31	Iqaluit	0.32	Calgary	1.38	31.44
Normalized MI Annual	1.10	2.66	0.73	Calgary	0.28	St Johns	2.94	66.24
Normalized MI Straube's	1.03	3.49	1.02	Winnipeg	0.33	St Johns	3.81	99.42
MI MEWS Annual	0.99	1.19	0.37	Edmonton	0.49	St Johns	1.67	36.98
MI MEWS Straube's	0.86	1.74	0.54	Toronto	0.39	St Johns	2.13	62.26

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Structural Performance Monitoring Technology and Data Visualization Tools and Techniques – Featured Case Study: UBC Tallwood House

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Abstract:

Wood structures such as the Wood Innovation and Design Center in Prince George and the UBC Tallwood House, an 18 storey, 53-meter-tall mass timber hybrid building are examples of new and innovative wood structures that encompass new construction techniques, unique materials and novel building practices. Empirical data on the condition of critical components and access to the real-time status of the structure during construction gives Architects, Engineers and Contractors critical information to make informed decisions to either validate or improve the construction plan. Data recorded during the life of the building helps validate the design decisions and proves the viability and feasibility of the design. Methods and practices used to monitor both the moisture performance of prefabricated cross laminate timber (CLT) as well as the vertical movement sensing of the building during and after construction are explored in this paper. Moisture content of the CLT panels has been recorded from manufacturing and prefabrication to storage, through transport and during installation and will continue throughout the service life of the building.

The calculated and expected displacement of the wood columns is scheduled to take several years as the structure settles, however a first-year analysis and extrapolation of the data was conducted. Monitoring during transport, storage, and construction proved that CLT panels were resilient to moisture issues while in the manufacturers storage, but prone to direct exposure to moisture-related problems regardless of the precautions taken on site. Despite construction during typical Pacific Northwest rain, informed decisions were made to ensure the panel moisture content could decrease to acceptable ranges before continuing to secondary construction phases. The moisture trends observed in the building were proportional to the control samples as both were subjected to similar environmental conditions.

Keywords:

Moisture performance, Vertical movement, Prefabricated wood

1. Introduction

The use of engineered wood products to build larger wood buildings is becoming more prevalent over recent years (Wang, 2015). As mass timber structures move to the forefront of sustainable design, construction methods to economically and continuously monitor these structures for key performance indicators are extremely valuable. This paper used research performed on UBC Brock Commons Tallwood House as a case study in an exploration of various remote monitoring methods with an analysis of the first year of data collected from the building.

Research was conducted to evaluate the moisture performance of prefabricated cross laminated timber (CLT) from the manufacturing plant, during transport and storage and during the construction process. A vertical displacement monitoring system was also instrumented throughout the building to gauge a better understanding of the short and long term settling of the timber structure throughout construction and active use. These areas of study were deemed important to gaining a broader understanding of using engineered mass timber as a common building material. Analysis of the data can be used for future

projects by designers, contractors, and building owners for which appropriate considerations will need to be made for their respective projects

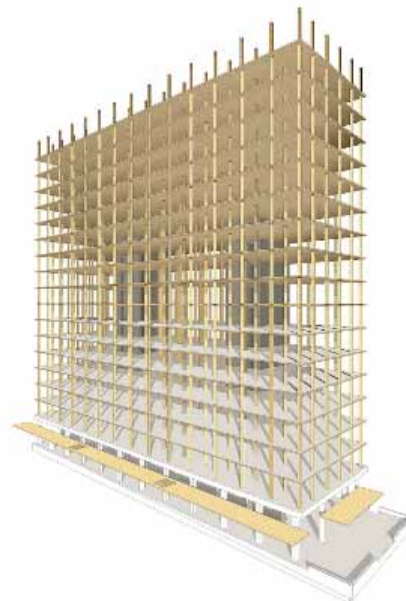


Figure 1. UBC Tallwood House (Image from Acton Ostry)

2. CLT Transportation Study

The Tallwood House project implemented a streamlined kit-of-parts approach to constructing the structural components of the building (Fraser, 2016). In this, the CLT panels were cut precisely to the dimensions required for installation. This included every opening and cut necessary for all aspects of the construction process (Sills 2016). Once each panel was manufactured they were coated with a urethane resin sealer, Miralite, on the panel faces as well as a wax coating on hole and end-grain surfaces for moisture control. Panels were transported to the construction site on the day they were intended to be installed. Instrumentation of the panels was done to observe the effects of changing conditions on moisture performance on the CLT through storage and transport.

Trips were made to the CLT manufacturing plant in Penticton, BC on May 5, 2016 and May 27, 2016 to outfit CLT offcuts with sensor arrays. Preparations were made to store and transport the offcuts in the same manner as the CLT panels to be used in the Brock Commons Tallwood House.

During the first trip, 2 large offcuts were outfitted with sensors, as well as 2 smaller CLT blocks. During the second trip, 6 large offcuts were instrumented and stored. All offcuts were coated with the same products and in the same manner as the full-size floor panels. The offcuts were then wrapped in plastic, stacked and stored alongside the full-size panels. Wood slats were placed in between each panel to increase airflow to the panels and prevent any potential moisture buildup, similar to how the full-size floor panels were stored.

3. Transportation Instrumentation

Sensor locations were chosen with the aim of acquiring a diverse set of data, avoiding interior joints, and avoiding material imperfections since probes hitting wood imperfections or interior joints could yield inconsistent results.

Detailed in Figure 2 a number system corresponding with drill depth was developed with #1 being the midpoint of the topmost layer and #5 being the depth of the bottom ply. Depths 1 and 2 utilized 200mm probes, depths 3 and 4 110 mm probes, and 5 a 40mm probe. Thermistors were installed to depth 3 at the center of the panel, and to depth 1 at the top face.

The CLT panel grain orientation changes with each layer. Probes were installed parallel to the grain of the testing layer to gather consistent data.

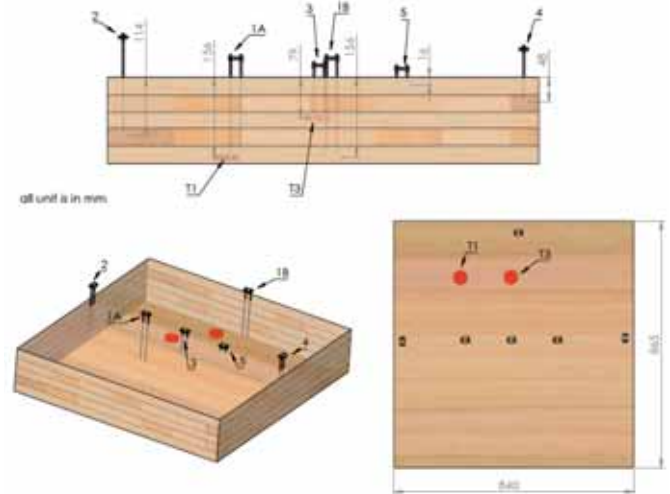


Figure 2. Probe Locations and Orientation



Figure 3. Instrumented Off-cuts May 7th, 2016



Figure 4. Off-cuts Stored outside next to Full Size CLT Panels



Figure 5. Six Additional Off-cuts Instrumented on May 27th, 2016

4. Transport

The offcuts were continuously monitored as they were transported from the CLT manufacturing storage facility in Penticton to the construction site at UBC. On site, long term storage was an impossibility due to site area restrictions. The process of shipment from the CLT manufacturing plant to being lifted for building installation occurred in a one-day window. Panels were stored on the trucks during transport in the precise order of installation (Sills, 2016). When panels arrived for installation, the protective plastic was removed, and placed on the supporting columns already installed in the building. From this point, the environment that they were stored in was no longer controlled and the CLT was exposed to environmental factors until the building was fully enclosed. To reflect this process accurately, transportation samples A and B were uncovered and left uncovered to be exposed to the rain and sun.

The timeline and path of travel for the transportation CLT samples are as shown Figure 6 and Figure 7. Samples were shipped with different floor panel shipments to create a diverse set of data with the possibility of varying environmental and logistical conditions.

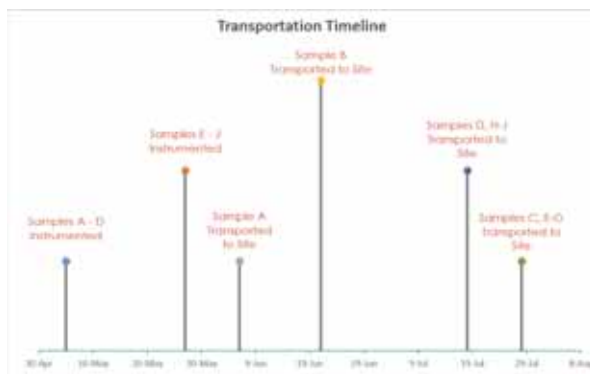


Figure 6. Transportation Timeline of Samples



Figure 7. CLT Transportation Path to Site

5. Data Collection and Analysis

Moisture and Temperature data were collected by the wireless data loggers connected to each panel. These devices stored data regardless of where the sample was located and transmitted the data to the Internet upon arriving on-site. Results from 60 moisture content sensors at varying depths and 20 temperature sensors are shown in **Error! Reference source not found.** and Figure 9.

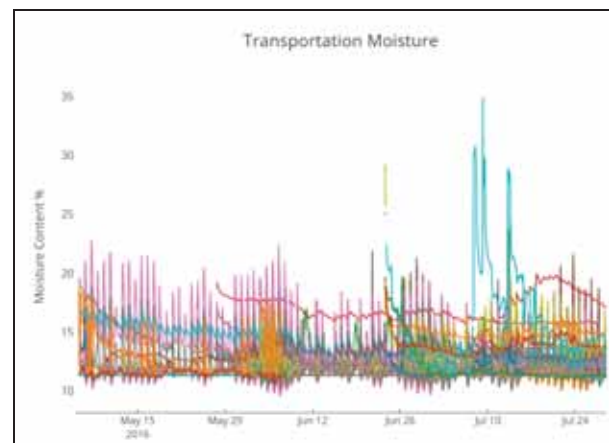


Figure 8. Transportation Moisture Data

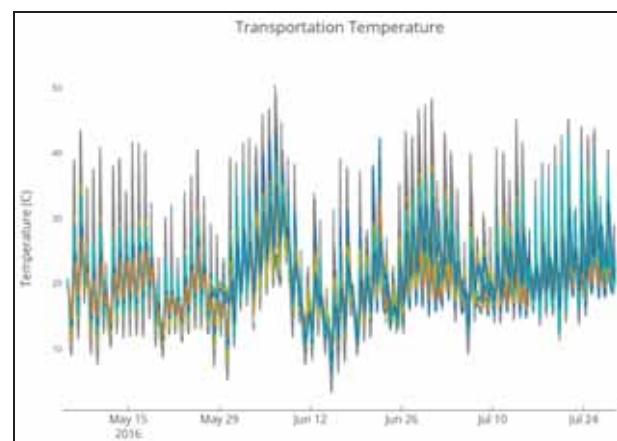


Figure 9. Transportation Temperature Data

Data from Transportation Sample A which arrived and was uncovered to reflect the conditions of the CLT of the structure showed the effectiveness of the processes the CLT manufacturer implemented while storing and transporting the CLT panels for this project. As seen in Figure 10 prior to shipping, moisture levels in the CLT samples stayed very consistent and were did not appear to be exposed to moisture

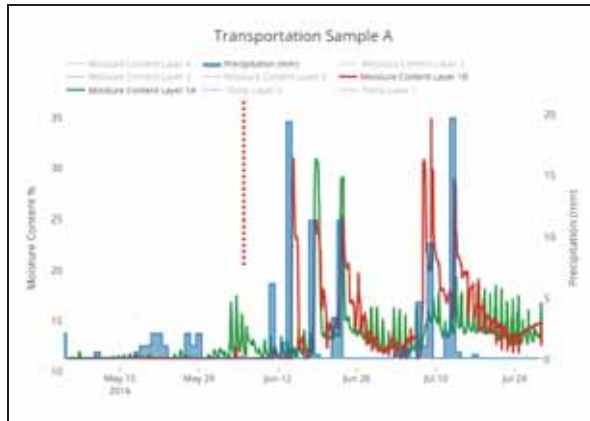


Figure 10. Analysis of Sample A During Transport

6. In Building Moisture

Sensors were installed into floors from below after the first layer of ceiling drywall was installed. Sequencing caused the data collecting units to be uninstalled and reinstalled a total of 3 times for each location. This re-installation took place to ensure the largest dataset possible. Detailed in this section of the paper is the methodology of transferring equipment from the transportation portion of the study and challenges which were overcome to gather the best picture of building moisture performance during construction. Points of interest and trends were discovered while monitoring the mass timber structure with over 300 sensors in a real-time cloud monitoring system. These sensors will remain in the building for its lifetime.

7. Monitoring Locations

Locations were selected with the intent of obtaining data representative of the majority of environmental and construction related factors that are present during different phases of construction. Instrumentation accounted for points where CLT was uncovered, cement pours took place, floors changing from passive to active heating as the seasons shifted from summer to winter and material staging in the East wing. Recording a dataset that will be representative of the entire building during occupancy was also considered as monitoring will continue throughout the life of the building. Every second floor was monitored and areas alternated between North-South and East-West locations as shown in **Figure 11** and **Figure 12**.

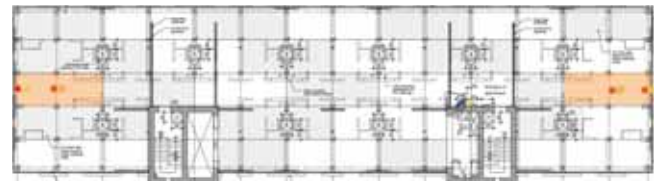


Figure 11. East West Monitoring Locations

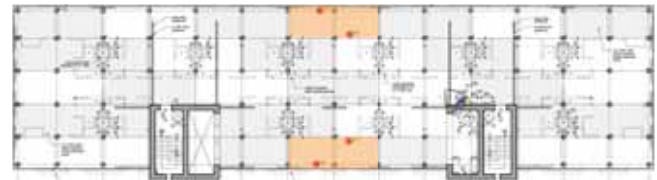


Figure 12. North South Monitoring Locations

8. Probe Depth and Orientation

Moisture probes were installed into the CLT panels in the Tallwood House onsite at UBC. Point Moisture Measurement Sensors (PMMs) were installed in alternating East-West and North-South panels on every second floor. The orientation of the PMMs and their depths were installed identically to the transportation study as illustrated in Figure 2.

Key considerations taken in the building study were that MC1B probes are in the plywood spline of non-edge locations. In edge installations MC1B measures moisture at the surface level as close to the edge of the panel as reasonably possible. These layouts are documented in the figures below

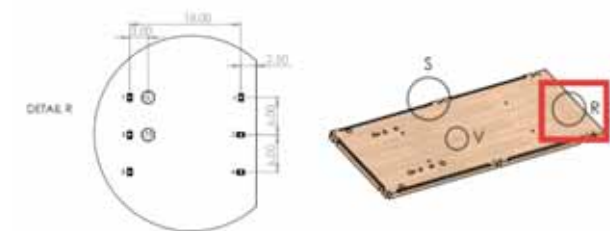


Figure 13. Edge Panel Mount Probe Locations



Figure 14. Plywood Spline Probe Locations

9. Building Element Completion

While monitoring the moisture performance of the CLT panels within the building, the panels were exposed to various events that ranged from rainfall before building enclosure to construction events as detailed in the table below:

Building Element	Start Date	End Date
Mass Timber Structure (L2 to L18)	6/6/2016	8/11/2016
Envelope Panels (L2 to L19 Parapet)	6/21/2016	9/8/2016
On-site Water Sealer (L3 to L18)	6/27/2016	8/19/2016
Concrete Floor Topping (L3 to L18)	7/4/2016	11/8/2016

Moisture performance of the CLT panels was analyzed with respect to these events as it was theorized that the CLT panels moisture levels would rise with the completion of the concrete floor topping. However, unless direct precipitation was in contact with the panels, the moisture levels did not change substantially. In event of direct moisture contact CLT panels would then quickly dry to acceptable levels. With the completion of the on-site water sealer used to improve the moisture protection of the CLT panels on-site and envelope panels, the overall moisture performance of the CLT panels became much more resilient to moisture. Year-long moisture performance of one location of the CLT is detailed in Figure 16.

10. Data Collection and Analysis of Full Building Moisture

As discussed in the transportation study and the previous section, the CLT panels within the building dried to acceptable moisture levels during the year-long monitoring. While collecting data during construction the data-collection units had to be removed and reinstalled several times to work within the schedule of other contractors. This process can be refined in the future with increased conversation between contractors and involvement with the sequencing schedule. In Figure 15 CLT moisture performance after an exposed rainfall event is shown

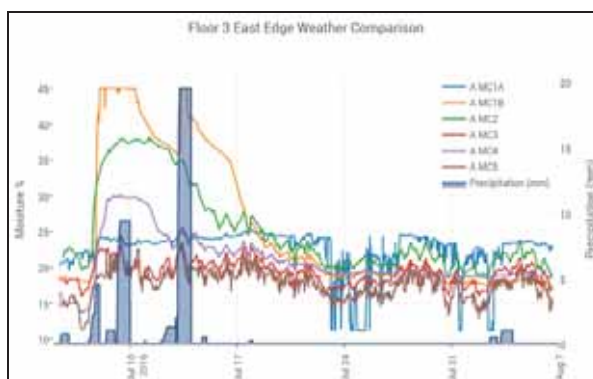


Figure 15. CLT Moisture Performance After Exposed Precipitation Event

In Figure 16, moisture data collected over the course of a year is shown with precipitation as represented by the the blue bars. Despite periodic precipitation, the CLT continued to dry during construction and after

the building had been closed. The red area is a gap in data due to removal and reinstallation of the data collection unit to work around other contractors.



Figure 16. Year Long Moisture Performance

11. Vertical Movement and Compression CLT Monitoring

Timber constructed buildings are susceptible to vertical movement due to the inherent deformation and compression of wood components and building settlement (creep). The construction of an 18 storey, 53-meter building presents an excellent opportunity to evaluate the vertical movement of a building of this magnitude.

Wood components of the building are as follows:

Glulam Columns: 78 glulam columns per floor except level 18, equating to 1302 columns in the building.

CLT Panels: 29 5-ply panels per floor, equating to 464 panels on 16 floors equating to a weight of 954 tons.

Total volume of wood in the building is 2233 cubic meters

The total measured deflection will be used to validate the calculated vertical movement allowing engineers to assess the impact on provisions made for the axial column shortening. The main concerns of axial shortening are the impact on vertical mechanical services as well as movement between the wood structure and concrete core (Fast and Jackson, 2017).

The axial column shortening was calculated to be 48mm. Of this, an estimate of creep and joint settlement is 12mm as shown in Figure 17. (Jackson, 2016)

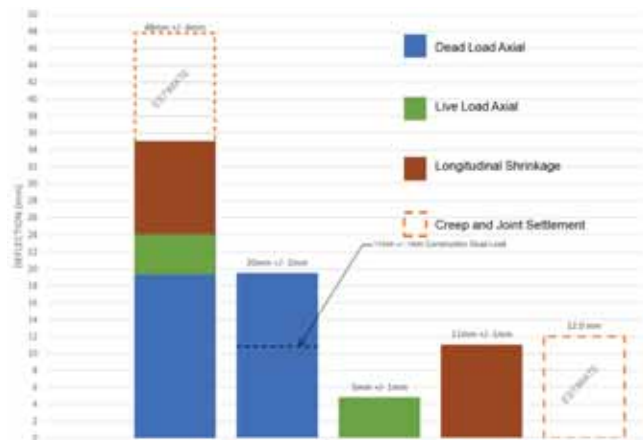


Figure 17. Column Shrinkage Estimation Calculated (Jackson 2016)

The difference between the axial concrete core shortening and the timber shortening is calculated to be 24mm. Provisions for axial shortening were mitigated by offsetting the connections for the CLT slabs so that they will naturally align after the building settles. (Jackson, 2016)

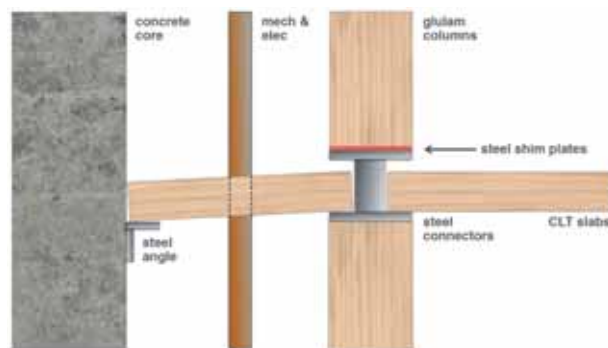


Figure 18. At Time of Construction

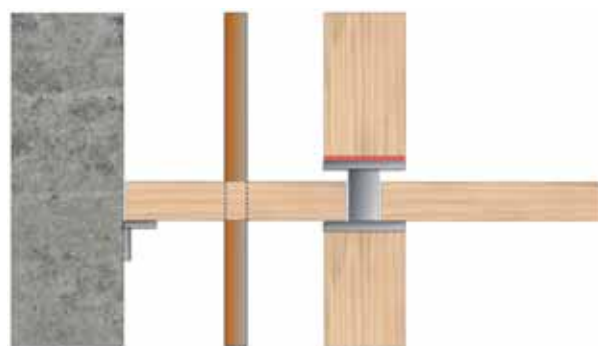


Figure 19. At a Later Date

12. Methodology

SMT and FPInnovations published the methodology for Vertical Movement monitoring in ASTM publication Volume 41, Issue 4 (Wang et al., 2013) titled Monitoring of Vertical Movement in Four-Storey Wood-Frame Building in Coastal British Columbia.

Several buildings were instrumented using this technology. The same instrumentation and methodology was applied to the UBC Brock Commons Tallwood House.

The measurement method consists of using a string pot sensor that contains a cable actuated position sensor connected to a spring loaded spool. The string is elongated using downrigger stainless steel non stretch cable and connects from the base of a selected column to the top of the floor above capturing the compression of the CLT and wood column.

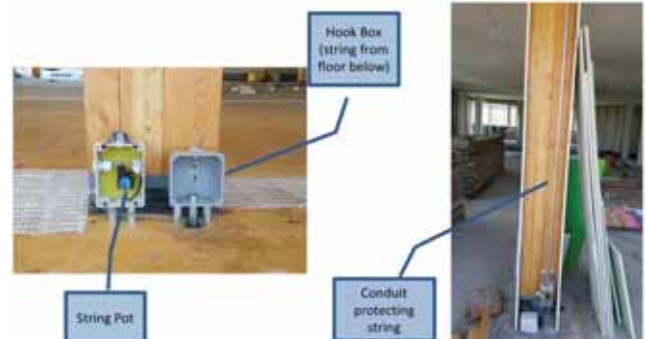


Figure 20. String Pot Installed in Structure

CLT columns from the base to the floor above were instrumented on the lower four inner floors and an all exterior columns extending up all 18 floors. The locations are shown in Figure 21 and Figure 22.

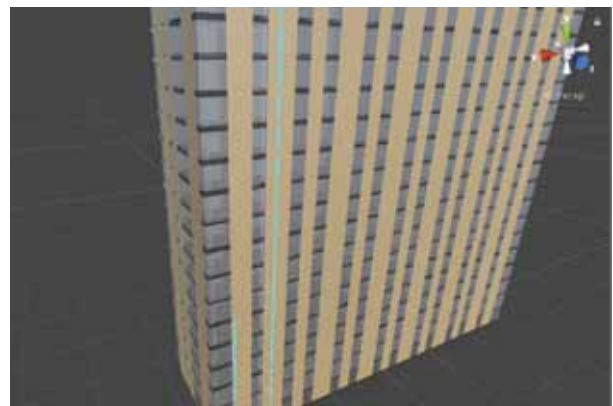


Figure 21. String Pot Locations along side and corner



Figure 22. String Pot Locations

13. Results

Upon commissioning, the sensors started at 0 mm displacement; positive displacement indicates there was an expansion, most likely due to the shoring; negative displacement represents vertical compression. Figure 23 shows the vertical displacement of selected string pot sensors during construction. Vertical displacement sensors were disturbed by shoring used to support outriggers during construction.

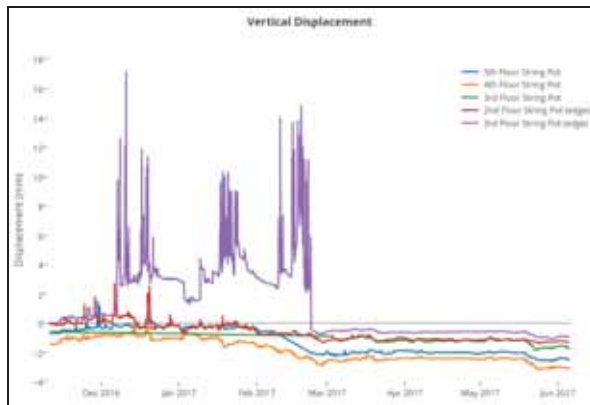


Figure 23. Vertical Displacement Sensor Data

Floor	Displacement After Shoring Removed	Total Displacement June 2017
2 (edge)	-0.960 mm	-1.387 mm
3 (edge)	-0.567 mm	-1.077 mm
3	NA	-1.821 mm
4	-2.577 mm	-3.182 mm
5	-2.052 mm	-2.604 mm

14. Data Collection and Analysis of Vertical Displacement

The shoring adversely affected the string pots while it was installed however after it was removed it did not appear to offset or skew the measurements. The edge columns and inner columns tracked each other as expected and the displacement on the outer column was less than the inner column as expected. Approximately 1mm displacement was observed on all floors in May 2017, this occurred when the window and façade details were completed on the end units after the outriggers were removed.

Displacement data from all 17 floors will be collected and compared with the compression models. Additional compression is expected to occur once the building is fully occupied and actual and dead loads are applied. In future large scale mass-timber buildings, columns closer to the core will be monitored as it is evident the load on the inner columns will experience more load than the edge columns.

15. Visualization Techniques

One of the most important aspects of structural health monitoring is disseminating and understanding the data collected. This involves identification, comparison, and correlation tasks which are performed on vast amounts of spatially embedded sensor data recorded over time (Gennady Andrienko and Natalia Andrienko, 2005). The datasets collected contain challenging features including big data with spatio-temporal attributes. The ability to browse this data using a classical interface is available where sensors can be selected, data can be viewed and sensors can be grouped and graphed together. In addition to this, the ability to overlay sensors on a building drawing allows a user to identify the sensor location and helps in understanding the situational awareness around the sensors.

Two data presentation methods were implemented as part of this project: Augmented Reality and Virtual Reality. These methods will make sensor exploration and analysis more intuitive and interesting. By creating data analysis tools that are visually accessible and digestible to the bulk of the general population, living labs have become interesting to much more than just building scientists and researchers. Creating interactive tools can spark an interest in education and awareness on sustainable construction and innovative design. These presentation methods also form another branch of research and development centered around IoT and big data solutions.

Analytics

Using standard data analysis tools such as sensor overlays and graphing tools, areas of interest can be easily identified and data trends pertaining to these areas further analyzed using standard graphing tools as shown in Figure 24.

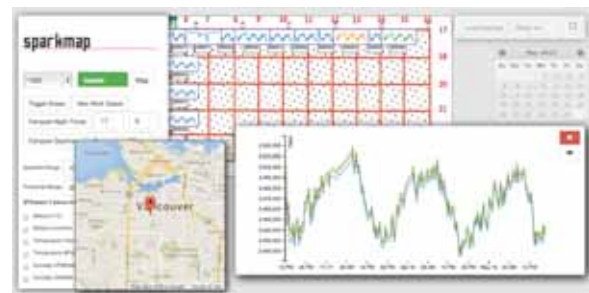


Figure 24. Analytics Graphing Interface

Augmented Reality

Using a custom Smartphone app, data can be extracted from embedded sensors and overlaid over the image in a smartphone display. Once the app recognizes a unique identifier in the camera viewfinder, data pertaining to the sensor location is accessed from the cloud based server and populated

on the image, displaying real-time data over the view shown on the camera. This creates a highly interactive environment for educators, students, and visitors of the space. Being able to tangibly associate building assemblies with real-time data with a mobile device also creates an opportunity to very easily investigate the surroundings of the instrumented areas.



Figure 25. Augmented Reality Interface

Virtual Reality

The BIM model for UBC Tall Wood House was ported into a gaming software engine, Unity. Sensors were populated throughout the 3D model. Using common gaming controls, users are able to virtually walk through the building and select sensors to view their data. Multiple sensors can be selected, graphed and compared while walking through the building in a virtual environment. Creating a contained environment marrying the real-time sensor data and the BIM model allows for on site and remote exploration of the structure. This allows students and visitors to interact with sensors in restricted and hard to reach areas from a centralized dashboard. For researchers and Building Scientists, this creates an environment to visually investigate both the 3D model, and its corresponding data in a singular analysis ecosystem.



Figure 26. Virtual Reality View of Hallway at Tall Wood House

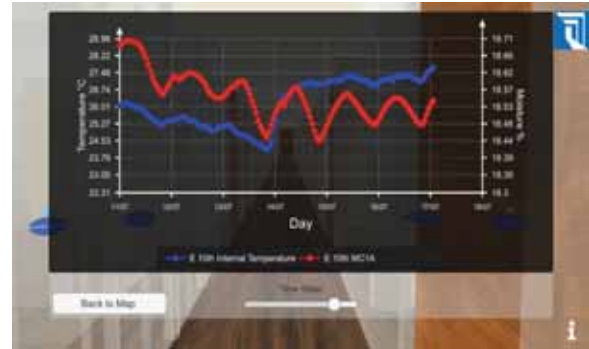


Figure 27. Sensors can be Selected and Graphed



Figure 28. AR External View of Brock Commons

16. Conclusions and outlook

The UBC Brock Commons Tallwood House presented a unique opportunity to instrument a structure with forward thinking in design and construction. Gathering imperial data during the various stages and conditions facilitated the assessment of the processes used and allowed adjustments for continuous improvement during the construction process. The moisture mitigation of the CLT panels worked well and despite wetting during construction the panels dried to acceptable moisture levels during the year long monitoring process. The vertical displacement of the edge and inner columns tracked each other and settled as expected. The lessons and information gathered from the structure thus far and in the future as the building will be continuously monitored for its lifetime will prove to be invaluable to similar innovative projects in the future.

Acknowledgements

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Civil Structural Forms and Extreme Loading

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Abstract:

By 2050, 70% of the world's population will live in cities. Structural engineers envision, design and construct the bridges and long - span buildings those city dwellers depend on daily. The construction industry is one of most resource - intensive sectors, and yet our urban infrastructure continues to be built in the massive tradition in which strength is pursued through material mass. In contrast, the research at the Form Finding Lab at Princeton University has focused on structural systems that derive their strength from their curved shape, dictated by the flow of forces. As a result, these structures can be extremely thin, cost - effective, and have a smaller carbon footprint. In this paper, an overview is giving of two research projects, one on adaptive facades and one on earthen shell structures, that address the question "What is the relationship between form and efficiency in structures under extreme loading?"

Adaptive building skins: Adaptive building skins act as active climate filters and moderate the influence of variable weather conditions on the building's interior environment. However current adaptive systems rely on complex mechanical hinges and actuation devices that increase construction and control complexity as well as cost. Therefore, our research seeks to simplify and tailor these shape-shifting systems through the application of botanic principles. The core idea for the research is to interpret, upscale, modify, and tailor elastic deformation mechanisms found in plants to mechanically less complex adaptive building skins.

Force-Modeled Shell Forms for Seismic Regions: Existing thin shell structures, such as Félix Candela's shells (Mexico City, Mexico, 1958) have empirically proven to be extremely resilient while surrounding structures collapse under earthquakes. However, very little research has been performed to understand and exploit the excellent structural behavior of large span shell structures under extreme loads. A numerical design methodology is presented for generating shapes for shell structures made of materials with low compressive strength in seismic areas.

Keywords:

Earthquake, Adaptive, Structural Forms

1. Introduction

Master builders throughout history have made significant strides in exploiting forms to enclose three - dimensional (3D) spaces, to provide shelter and protection (e.g. the Pantheon dome, Rome, Italy, 126 CE), or to bridge two - dimensional (2D) voids, such as water and roadways (e.g. the footbridges by Robert Maillart, Toss, Switzerland, 1932). In absence of numerical prediction methods, they resorted to trial and error construction practices or structural theory to establish a good enough structural form. Today, structural engineers are often excluded from the initial building design process and are introduced into the picture only once the form has been fixed. Pier Luigi Nervi, structural engineer and designer of the exquisite Little Sports Palace (Rome, Italy, 1958), stated: 'Resistance due to form, although the most efficient and the most common type of resistance to be found in nature, has not yet built in our minds those subconscious intuitions which are the basis for our structural schemes and realizations'. In this paper we present two approaches to generate structural thin forms for unusual loading conditions; one based on biomimicry for adaptive systems and one based on

hanging chain form finding for rigid large span shells subjected to earthquake loading.

2. Efficient movements for adaptive structures through the study of plant movements

Adaptive structures, compliant mechanisms and plant movements share similar strategies to create efficient movements. They all rely on kinematic amplification, which is the capacity of a mechanism to produce more displacement than was initially inputted by an actuator. The kinematic amplification is also called distance advantage and is defined as the ratio of output displacement to input displacements in a kinematic system. The amplification ratio measures the efficiency of structures at transforming the input actuation into large displacements. High amplification is sought for by designers to create more efficient deployable and adaptive structures, for example to adopt efficient kinetic skins to regulate the indoor climate in buildings.

As shown in table 1, plants use the same mechanisms as some of the most advanced engineered mechanisms. Biology does not produce perfectly optimized solutions, just solutions good enough to fulfill a task. There is, however, much to be

gained from studying the diversity of mechanisms in plants. Engineers can improve on nature's mechanical systems to make them more efficient.

Plants implement purely mechanical strategies to amplify the movements. First and foremost, differential expansion within a layered-solid is the most common strategy for movements of plants. In active movements, the organ called pulvinus performs differential expansion based on turgor pressure variations. In its most advanced form, the pulvinus achieves spherical, two degree-of-freedom, movements. In simpler variations, pulvinus movements are planar, one degree-of-freedom. In passive movements of fruits and seeds, anisotropic expansion of dry cells caused by external environment parameters such as diurnal cycle hygrometric variations generate large displacements. Mechanical displacement-amplification strategies such as lever action and torsional buckling enable flower passive movements. Pollinators actuate the mechanism by their weight or attempt to collect nectar. The actuation in passive movements therefore comes at no metabolic cost for the plant. In functions requiring speed, such as predatory nutrition, pollination by deception or release of seeds, elastic instabilities and geometric effects allow the release of energy powering the movement. The compliance of the material allows the large shape variations between the different states of the mechanism.

The mechanical characterization of the movements of carnivorous plants constitutes a large source of unexplored information about plant movements. In analogy, manmade mechanisms rely on the material properties and geometry of their constituents for actuation. Motorless, hingeless and wheel-less actuation is based on material deformations (expansion, incompressibility) resulting in small amplitude displacements. These mechanisms therefore frequently resort to a movement amplification, and parallels can be drawn with plant amplification strategies. For manufacturing reasons, these deformation-based actuation patterns are widespread at micrometer scale, which is why various examples are drawn from the field of micro-electro mechanical structures. One can distinguish four displacement amplification strategies: a geometrical strategy, controlling the material properties like stiffness, anisotropy or thermal expansion coefficients, the swelling and shrinkage, and the storage of energy. These strategies can be found in plant movements. Plants and manmade mechanisms often implement various displacement strategies at the same time, and each one can have its own function for the output movement. The combination of amplification strategies can also allow other mechanical features such as for example the stability of some zero-energy positions. These couplings of strategies have been assembled into table 1. The bilayer amplification was found to be particularly efficient and can be highlighted in relation to manmade mechanisms as it reaches a kinematic amplification ratio (140) of an order of magnitude higher than the other listed

strategies. This clearly provides a parallel between engineered moving devices and moving plants: the bilayer effect caused by the differential expansion of cells or by the cell anisotropy in hygroscopic tissues is also the most widespread amplification mechanism in plants, probably because it is the most efficient.

The plant's microscale mechanical properties (mainly a stiff cell wall and the turgor pressure) and the entanglement of appropriate structural organizations at each scale make of plant tissues a genuine 'smart material'. They account for a variety of advanced structural features, some of them being usually avoided in engineering. Mechanical couplings like torsional buckling, and elastic instabilities like the snapthrough phenomenon, testify to the great diversity of mechanisms that can be encountered in the plant's world. Their movements come with different speeds, kinematics, functions (e.g. sun-tracking, growth, reproduction, predation), and can be passive or active with numerous different triggers. This approach lends itself to the development of structural forms (such as adaptive facades) that are efficient in their energy and material use.

3. Force-Modeled Shell Shapes for Seismic Regions

Lightweight shell structures tend to behave well during earthquakes due to their high stiffness because of curvature, and low mass. This combination often results in high fundamental frequencies limiting dynamic amplification [11]. However, the potential for the construction of such shells in seismic regions has barely been researched. To account for the large horizontal loads and anticipated bending moments, we developed a form-finding methodology that considers an equivalent horizontal earthquake load from the start of the shape finding process. The method provides antifunicular shapes that allow the development of a compression-only load path under combined gravity and horizontal loading, while not relying on any tension capacity of the material. To efficiently build such form-found shells, while retaining the benefits of low mass, it is suggested to implement the obtained forms as interconnected double-layer thin shells, so that a thrust network can form over a wide depth of the structure.

The proposed method relies on the no-tensile model developed by Heyman [5]: crushing does not occur (1), the tensile strength of the masonry is negligible (2), and sliding between blocks does not occur (3). When these assumptions hold, a structure is self-supporting as long as one equilibrium compressive load path network fits within the geometry of the masonry under its own weight [1]. The theorem can be expanded to a combination of gravity loads and horizontal loads and has been used to find the shapes of arches under earthquake loading [10]. The dynamic seismic loading is approximated by an equivalent horizontal load due to an acceleration, the peak ground acceleration (PGA), which is proportional to the gravity load.

Couplings of strategies	Variation of material properties	Geometrical strategies	Energy storage	Fluid incompressibility / Swelling and Shrinkage
Variation of material properties		<i>Aldrovanda vesiculosa</i> [13]: Turgor bilayer action coupled with double curved shell bending	Explosive seed dispersal in <i>Impatiens</i> [3]: material incompressibility and prestressed beams	Fruits and seeds detached from the vascular system: increase of material volume by hygroscopic material [6, 17]
Geometrical strategies	Flectofin [9]: variation of the composite properties and amplification through shape changes.		<i>Dionaea muscipula</i> [13]: Elastic instabilities and snap-through mechanisms	Fast movement of Stylidium [4]: Geometric effect of progressive reversal of transversal curvature in a longitudinally curved beam
Energy storage	Bistable steel tape [7]	Snap-through mechanism [2]: amplification through shape changes & energy storage		Pulvinus [16]: actuator implementing bilayer effect for two degrees of freedom
Fluid incompressibility / Swelling and Shrinkage	Hygroscopic pavilion [14]: bilayer mechanism & hygroscopic swelling	Array of inflatable cells connected by valves [15]	Fluidic origami [8]	

Table 1 Plant and engineering mechanisms classified by strategy

The 2D idea of an inverted hanging chain fitting into a masonry arch [12], can be expanded to an inverted hanging net in 3D. If such an antifunicular net fits within the structure's geometry under the combination of self-weight, and horizontal acceleration, the masonry shell will be stable. In our novel proposed form-finding method the process starts with finding hanging nets under gravity and horizontal accelerations, which is done by using cable elements in a dynamic relaxation routine.

The shells are represented digitally by discretizing the surface into a network of springs connected at nodes with free rotation. Gravity and earthquake loading (lateral load of 0.3 g) are applied at the nodes (fig 1 step 1). This system behaves like a cable net and can act in pure tension. When inverted, it creates an antifunicular network in compression. The interactive computation of the shell shape starts from a flat mesh of springs with assigned supports and uniform loads. First, a net under earthquake loading is found for one loading direction (fig 1 step 2), it is repeated under the same horizontal loads acting in a different direction (fig 1 step 3). Eight directions for the horizontal loads are considered as well as a case under only gravity loading (fig 1 step 4). This leads to a set of antifunicular nets that are superimposed (fig 1, step 5), after which the envelope of all solutions is taken (fig 1, step 6). If the bottom and top layers are considered as the boundaries of a continuous shell with varying thickness, one can find an antifunicular net that fits within the top and bottom layers under the design loading.

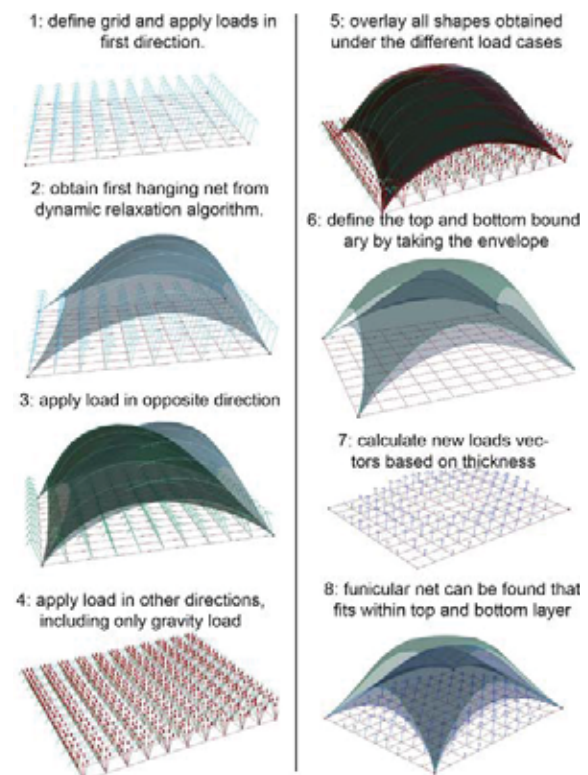


Figure 1 – The form-finding procedure explained step by step

To obtain a representative net, the initial load assigned to each node needs to be updated as the thickness (and thus the loads) has changed accordingly. The values of the initial loads are therefore multiplied by the normalized magnitudes of the distance between the bottom and top layer, leading to a new non-uniform load distribution (fig 1, step 7). An antifunicular net can then iteratively be found so that it fits between the top and bottom layer, assuring the shell will stand under the design horizontal load (fig 1, step 8).

Applying this methodology to a square starting grid with different boundary conditions leads, for example to the 6 shell shapes displayed in figure 2.

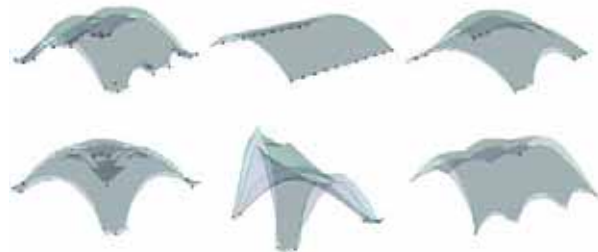


Figure 2 – Variety of double layer shells obtained through the form-finding procedure

This approach generates slender efficient building forms that are resilient in earthquake prone regions.

4. Conclusions and outlook

The construction industry is one of the most resource-intensive industries. With the goal of obtaining material efficiency in civil forms, we demonstrated two approaches; one based on biomimicry and one based on form finding techniques, to attain adaptive forms and resilient large-span building forms.

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A brief background on climate models: the source of future climate information

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Abstract:

Climate affects almost every aspect of our life - the food we eat, the way we dress, the amount of energy we use to heat and/or cool our homes, and the way in which we design our civil infrastructure. Almost every aspect of the design of civil infrastructure is affected by weather and climate. Consider the design of public storm water systems that depends on rainfall frequency and intensity, the design of bridges that depends on maximum river or sea levels, and the size of the hydroelectric reservoirs and turbines that depends on river streamflow. Most civil infrastructure is designed for some return interval of extreme events. Bridges, for example, are often designed to withstand storms that have a probability of occurring only once or twice every 100 years. But since climate is changing, the historical climate cannot be assumed to be an accurate predictor of the future climate. Analysis using results from Earth system models and our physical understanding of the climate system suggest that the frequency of many extreme events is expected to increase globally. For example, extreme heavy precipitation events are projected to increase in all high-latitude regions including Canada. Clearly as climate is changing, we as a society and our infrastructure need to adapt. This paper provides a brief overview of climate and Earth system models, how climate change simulations are typically performed, and what kind of data are available from climate and Earth system models for use by the impacts and adaptation community. As with other types of models, there are caveats associated with the results produced by climate models. This paper suggests best practices in context of making the best use of information available from climate models in light of uncertainty associated with their results and the uncertainty associated with future climate change scenarios.

Keywords:

Climate change, extreme events, return period, climate models, future scenarios

1. Introduction

The design of civil infrastructure from our houses and buildings to the design of hydroelectric turbines, and everything in between, are all influenced by climate. The design of civil infrastructure has to follow local codes that take into account the local climate. A simple example which illustrates this is the depth of foundation footings for buildings and decks. In warm climates, where frost rarely ever occurs, footings are typically placed at shallow depths of 6-12 inches, assuming the soil beneath is not settling. In cold climates, since frost depths are much larger, the footings need to be deeper so that frost heave during the winter months does not damage the structure that is being supported by footings. The minimum depth for footings in the “sunshine” state of Florida in the United States of America, for example, is 6-12 inches while in the state of Minnesota, which experiences cold winters, footings are required by code to be between 54 and 60 inches deep.

Projected changes in future climate imply that the historical climate cannot be assumed to be an accurate predictor of the future climate. The projected changes in climate need to be taken into account via

changes in codes and standards or some other mechanisms. Infrastructure codes are designed at all levels of governance: the First Nations, the municipal, the state or provincial, and the federal. Climate is taken into consideration also by engineers at private construction firms. However, engineers and designers responsible for updating of design codes are typically, and as would be normally expected, not familiar with climate models or their output. It remains a challenge how to transfer knowledge from the climate community to impacts and adaptation communities and professional communities of practice (in this case the civil engineering community) so that the climate change information simulated by climate models can be best used for updating building codes and design of civil infrastructure in general.

This paper attempts to familiarize the civil engineering community with climate and earth system models, their output, and provides advice for best practice in the context of using climate change information from climate models. It familiarizes the reader with uncertainties associated with climate model output and the uncertainties associated with future climate change scenarios.

Section 2 of this paper provides a brief introduction to the concept of climate change, climate and Earth system models, driving data used by these models and the output from these models. This section also describes typical simulations performed by climate models including those performed for the future for different climate change scenarios. Section 3 discusses caveats associated with the output from climate models, including biases and uncertainties in model output, and how these can be addressed to use climate model output for updating building codes or designing structures that require future climate information. Finally, conclusions are presented in Section 4.

2. Climate change and climate models

2.1 Climate change

As economies develop, their energy requirements increase [1] due to increase in per capita energy consumption and due to increase in population. In our case, this increased energy demand has been primarily met by increased burning of fossil fuels. About 80% of the world's energy needs are currently met by burning fossil fuels (World Bank, <https://data.worldbank.org/indicator/EG.USE.COMM.F.O.ZS>). The increased anthropogenic use of fossil fuels to meet our energy demands and the increase in agricultural area over the historical period to feed the increasing population has meant increased emissions of carbon dioxide (CO_2) and other greenhouse gases (GHGs) including methane (CH_4) and nitrous oxide (N_2O). CO_2 is the primary GHG responsible for most of the warming since the start of the industrial era. The increase in agricultural area over the historical period has led to a reduction in the area of forests and grasslands due to deforestation. This deforestation consequently changes the planet's land cover.

Year 1750 is generally accepted as the beginning of the industrial era because atmospheric CO_2 concentration generally varied between 276 and 283 ppm from 0 to 1750 AD and since 1750 atmospheric CO_2 concentration has been increasing gradually. Since 1750 the radiative forcing caused by CO_2 is the largest amongst all GHGs and other forcings [2]. Radiative forcing is the measure of the capacity of forcing agents to affect Earth's energy balance, thereby contributing to climate change. CO_2 is also a long-lived GHG with an atmospheric life time of 100-200 years, which basically implies that any CO_2 that stays in the atmosphere will stay there for a very long time. Together with slowly warming oceans in response to climate change this implies that climate change is irreversible at least at millennia time scale [3]. Fortunately, not all of the CO_2 that is emitted from the burning of fossil fuels stays in the atmosphere. The Earth's vegetation and oceans are quite effective in removing about half of the CO_2 that is currently emitted [4]. Had it not been for the carbon absorbed by our terrestrial biosphere and the oceans, the

current atmospheric CO_2 concentration wouldn't be around 400 ppm as it is now, but much higher at around 520 ppm.

The rising concentrations of GHGs not only warm our planet by trapping the outgoing longwave radiation but they also change the general circulation of the atmosphere. The earliest unequivocal signs of climate change have been the warming of the air (see Figure 1) and ocean, and thawing of land and melting of ice in the Arctic. But several lines of evidence show that over the past few decades the tropical belt has been expanding. This movement of large-scale atmospheric circulation systems towards the poles, such as jet streams and storm tracks, could result in shifts in precipitation patterns affecting natural ecosystems, agriculture, and water resources [5].

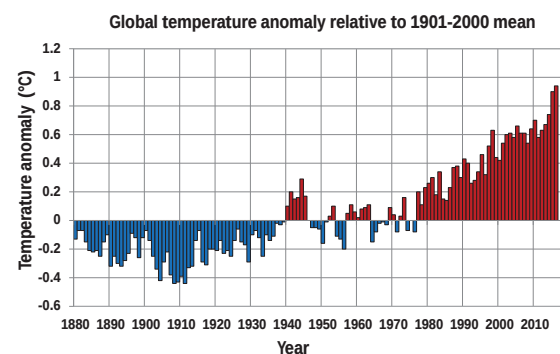


Figure 1: Global-mean temperature anomaly (or change) relative to average over the 1901-2000 period. The last year plotted is 2016 and is the warmest year on record and 0.94 °C warmer than the 1901-2000 average. The data are obtained from <https://www.climate.gov/maps-data/dataset/global-temperature-anomalies-graphing-tool>.

2.2 Climate models

The understanding of changes in Earth's climate in response to increasing concentrations of GHGs due to anthropogenic activities is based primarily on global climate models, also referred to as general circulation models (GCMs). GCMs represent the physical processes and interactions between the atmosphere, ocean, cryosphere (ice and snow) and land surface using a numerical mathematical framework and they are based on general principles of fluid dynamics and thermodynamics. GCMs simulate the climate using a three dimensional grid over the globe (Figure 2), typically with a horizontal resolution of between 100 and 300 km, 30 to 40 vertical layers in the atmosphere, 3-10 layers in the soil and bedrock, and 40 to 50 layers in the oceans.

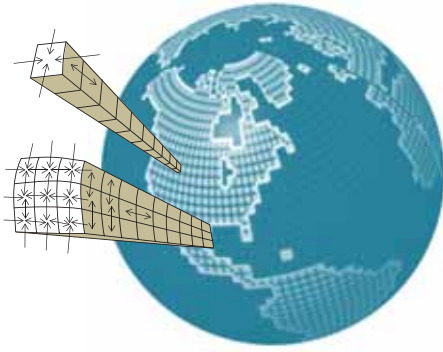


Figure 2: An illustration of the three dimensional grid in global climate models. The arrows indicate the movement of fluxes both horizontally (between columns) and vertically (between layers).

Over the last decade or two, the GCMs have evolved into Earth system models (ESMs) by inclusion of biogeochemical cycles (primarily the carbon cycle) and atmospheric aerosols (primarily sulfur). A biogeochemical cycle is a pathway by which a chemical substance moves through both the biotic (biosphere) and abiotic (atmosphere and hydrosphere) components of the Earth. Aerosols are minute particles suspended in the atmosphere. When these particles are sufficiently large, we notice their presence as they scatter and absorb sunlight. The inclusion of carbon biogeochemical cycle related processes in ESMs has meant that terrestrial vegetation in these models can respond to changes in atmospheric CO₂ concentration, and so can the oceans. This allows us to model the fate of additional carbon that is put into the atmosphere as a result of CO₂ emissions from burning of fossil fuels.

With all their physical and biogeochemical processes, ESMs are able to model the physical, chemical and biological states of their atmosphere, land and ocean components and their response to external forcings such as increased CO₂ emissions, changes in the solar intensity, or even large scale tree plantations or deforestation. The physical state of the atmosphere, for example, is described by temperature, pressure, humidity and wind velocity at each and every grid cell on the surface of the Earth and each and every level in the atmosphere. Over land, the physical state of the land surface is characterized by soil temperature, amount of liquid and frozen moisture contents in different soil layers that the model represents, any snow present on the surface and its thickness and coverage, the presence/absence of vegetation (and its height, biomass, rooting depth and other characteristics). The physical state of oceans is characterized by their temperature, salinity and currents at the surface and at different levels, and the presence/absence of sea-ice and its thickness and coverage.

2.3 Model simulations

While climate and Earth system models can be used to ask a wide range of “what if” questions by performing specialized simulations, there are three basic type of simulations that are typically performed with climate and Earth system models that are most relevant to assessing impacts and informing adaptation.

1. Pre-industrial simulation (corresponding to year 1750 or 1850)
2. Historical simulation (e.g. from 1851 to present)
3. Future scenarios simulations (e.g. from present to 2100)

The pre-industrial simulation simulates climate corresponding to the pre-industrial times when atmospheric concentrations of CO₂ and other GHGs were much lower. In this simulation, the concentration of GHGs, land cover, emissions of atmospheric aerosols and other forcings are all set to their pre-industrial levels, typically corresponding to year 1750 or 1850. This simulation is run for several hundreds of years and, while there is year to year variability in simulated climate, the long term climate in this simulation should remain stable. Even in the absence of any external forcing no two years are exactly the same because of the natural variability of the climate system. But since there is no external forcing in this simulation the model climate doesn't show a systematic increase or decrease (called a drift) in temperature and other climate variables. This simulation serves as a control simulation and historical and future simulations are typically compared to a pre-industrial simulation in terms of global changes but also changes in geographical patterns.

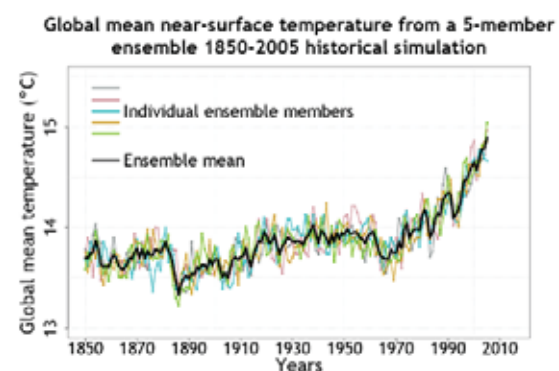


Figure 3: Global mean near-surface temperature simulated by second generation Canadian Earth system model (CanESM2) [6] over the historical 1851-2005 period. Results shown are from the 5-member ensemble. Also, shown is the ensemble mean.

A historical simulation is launched from the pre-industrial simulation. Any year in the pre-industrial

simulation can be used to launch historical simulations because they all represent the pre-industrial climate. Typically, 5-10 (and sometimes more) historical simulations are launched (or initialized) from different years of the pre-industrial simulation. Each simulation is different from each other in terms of year-to-year climate but over the long historical period they all show similar increases in temperature associated with increasing concentrations of GHGs. This is shown in Figure 3. The results shown are from the second generation Canadian earth system model [6] (CanESM2) from the Canadian Centre for Climate Modelling and Analysis (CCCma) which is a section of the Climate Research Division (CRD) of Environment and Climate Change Canada. Each historical simulation in this ensemble of historical simulations is thus an individual realization of the historical climate. A related note of caution here is that none of the historical simulations can be expected to correspond to the specific climate observed historically at corresponding dates. Only the overall statistical characteristics of climate variability should be similar to those seen in the observations. The reason for this is because the historical climate that we have observed is also an individual realization of the highly nonlinear (and therefore chaotic) climate system. Since we do not have a perfect state of the climate in 1850 (or any other year), from which to initialize a perfect climate model, we cannot reproduce the perfect year to year variability with any climate model. The same chaotic behaviour underlies the roughly two-week limit on the useful horizon of weather forecasts. Typically, an ensemble-mean is calculated to separate the forced signal due to the increasing atmospheric concentration of GHGs (and other forcings) from natural variability and to increase the signal-to-noise ratio. The historical simulation is forced not only by increasing concentration of GHGs but also by increasing emissions of aerosols (soot) (also associated with increasing use of fossil fuels), and changes in land cover (associated with deforestation to increase area under agriculture). In addition to these forcings, climate models also need information about solar activity and volcanic forcing which affect the climate. All of these forcings affect the climate in different ways but, of course, the primary response of the climate system over the historical period to all forcings has been warming.

The results from historical simulations are compared with observations of historical changes in globally averaged temperature but also geographically and seasonally varying distributions of observed temperature, precipitation, and other climate variables. Several other comparisons with observations are also performed. These comparisons help to evaluate model results and assess model limitations.

Finally, the future simulations are based on several forcing scenarios. Future scenarios typically range from a business-as-usual high emissions scenario to

a low emissions scenario (which aims to keep the projected global warming below 1.5 to 2.0 °C above the pre-industrial levels) with several scenarios in between with mid-range emissions.

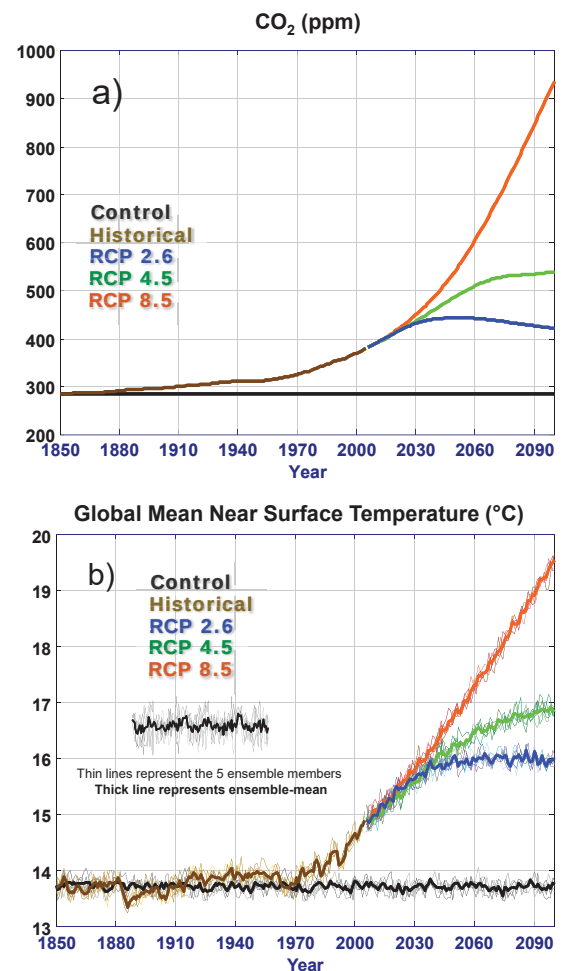


Figure 4: Global mean atmospheric CO₂ concentration (a) and the simulated near-surface temperature (b) from CanESM2 [6] for the historical period and three future scenarios (RCP 2.6, RCP 4.5, and RCP 8.5). Also shown is global mean temperature from the control simulation of CanESM2. The historical simulation corresponds to the period 1851-2005, and the future simulations correspond to the period 2006-2100.

The future emissions scenarios are not put together by the climate community but by the environmental and energy policy analysis community using integrated assessment models (IAMs). IAMs consider the social and economic factors that drive the emission of greenhouse gases using a coherent and consistent description of how a future society may operate with a given culture towards fossil fuel consumption. For a given future scenario, IAMs provide not only anthropogenic emissions and concentrations of CO₂, but also CH₄, N₂O and other

GHGs, atmospheric aerosols, and an estimate of future agricultural areas. All these forcings are used to drive a climate model and obtain simulated climate data for the future. Just like the historical simulation is initialized from the pre-industrial simulation, the future simulations are initialized from the historical simulation.

The most recent future scenarios put together by the IAM community are referred to as representative concentration pathways (RCPs). Figure 4 shows the global mean atmospheric CO₂ and the resulting simulated near-surface temperature from CanESM2 [6] for the historical period and three future scenarios (RCP 2.6, RCP 4.5, and RCP 8.5). The numbers 2.6, 4.5 and 8.5 refer to the radiative forcing in each scenario in year 2100. The higher the radiative forcing the higher the warming. Note that the atmospheric CO₂ concentration by year 2100 in the business-as-usual RCP 8.5 scenario is more than 900 ppm; more than three times higher than the pre-industrial concentration of 278 ppm. In Figure 4b, the future simulations also have 5 ensemble members each. The spread across the ensemble members provides an estimate of natural variability for a given model. It is quite possible for different climate models to have different natural variabilities. Figure 4 shows global mean temperature changes of about 2.3 °C, 3.2 °C and 5.8 °C for RCP 2.6, 4.5 and 8.5 scenarios by year 2100 relative to the pre-industrial global mean temperature as simulated by CanESM2.

2.4 Geographical pattern of warming

The global mean temperature change shown in Figure 4 is not typically representative of the temperature change at any individual location. Figure 5 shows the geographical pattern of temperature change simulated by CanESM2 for the three future scenarios over the 2006-2100 period [7]. The changes are calculated as the difference between the decadal averages for the years 2006–2015 and 2091–2100.

Two primary observations can be made from Figure 5. First, the warming is higher over land than over oceans. Second, warming is higher at higher latitudes than at low latitudes. In fact, warming over high-latitude regions such as Canada is about twice the global average. The primary cause of this “Arctic amplification” is that melting of the Arctic sea ice and reduction in northern hemisphere snow cover leads to more absorption of the incoming solar radiation by the oceans and the land surface, and this enhances the initial warming. This is because the open water and land surface with no sea-ice and snow, respectively, are less bright than when they are covered with sea-ice and snow. The fraction of incoming solar radiation that is reflected back is called albedo. Amplification of warming at high-latitudes is thus caused by positive sea-ice albedo and snow-albedo feedbacks.

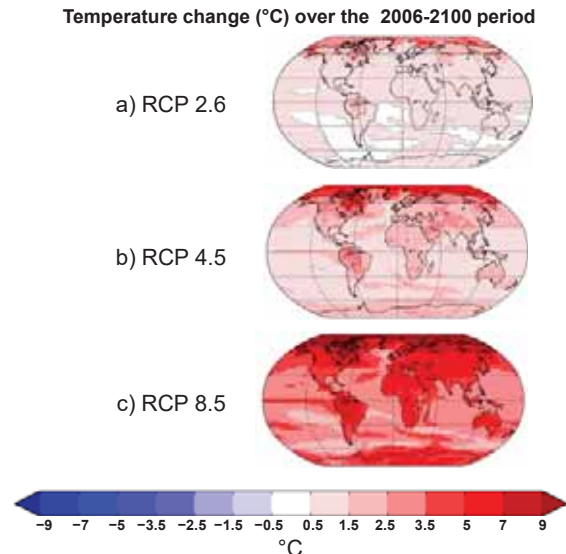


Figure 5: Geographical pattern of temperature change simulated by CanESM2 for RCP 2.6, 4.5 and 8.5 scenarios for the period 2006-2100.

2.5 Typical model output

Since most processes are modelled from first principles, and given the current complexity of ESMs, almost every physical climate-related variable imaginable can be output from ESMs including streamflow from major river basins. Model output from future climate simulations forms the basis of climate change information that is used by the impacts and adaptation community. Model variables that are commonly used by the impact and adaptation community are, of course, daily averaged temperature and precipitation. However, daily maximum and minimum temperatures, surface pressure, humidity, evaporation, solar radiation, soil moisture, snow depth, and wind speed are amongst most commonly downloaded variables.

In terms of temporal frequency, most data are archived at a monthly time resolution. A number of primary climate variables are also available at a daily time resolution. The actual model simulations are typically performed at a time step of 10-20 minutes so in principle it is possible to output model data at this time resolution. However, climate models typically do not archive data at such high time resolution because of the storage limitation imposed by the sheer volume of data that would be generated. There is also the question of whether outputs at this frequency lie below the “skillful scale” of models. As a general caution, just because an ESM simulates a given variable does not mean that it can be reliably used to address a given impacts and adaptation question.

2.6 Climate modelling community

The climate modelling community primarily organizes itself under the auspices of the Coupled Model Intercomparison Project (CMIP) which itself is organized under the World Climate Research Programme (WCRP). Every 7 years or so, the CMIP community designs the protocol for a range of climate model simulations (including pre-industrial, historical and future scenario simulations amongst many others). Climate modelling groups perform simulations following these protocols and the results are submitted to a central archive that is accessible to the general public. Results from CMIP simulations also contribute to the assessment reports of the Intergovernmental Panel on Climate Change (IPCC) which is the international body for assessing the science related to climate change. IPCC's mandate supports the United Nations Framework Convention on Climate Change (UNFCCC), which is the main international treaty on climate change. Results from the fifth phase of CMIP (CMIP5) [8], for example, contributed to the fifth assessment report (AR5) of the IPCC (<http://www.ipcc.ch/report/ar5>) which was published in 2013.

3. Climate models aren't perfect

While climate and Earth system models attempt to model a range of physical, chemical and biological processes from first principles they can only represent our best understanding of how our planet works and how it responds to external climate forcings. The true climate system is highly complex and so it remains fundamentally impossible to model all of its processes [9]. For instance, it is not possible to model the fate of each and every rain drop, or the evaporation of water from each and every single leaf on our planet's vegetation. Numerous physical, chemical and biological processes are parameterized – this means that their effects are represented by simplified approximations – since they cannot be modelled explicitly. There are over two dozen climate modelling groups around the world that perform simulations with their climate models. While based on the same basic principles, each group models (and parameterizes) the same process in slightly different way. The result is that different climate models respond to the same forcing in somewhat different ways. For example, the average global warming for the period 2081-2100, relative to 1986-2005, from 39 climate models for the RCP 8.5 scenarios varies from 2.6 °C to 4.8 °C (5% to 95% range) with mean $\pm$ standard deviation equal to 3.7 ± 0.7 °C [10]. The diversity amongst models is considered a healthy aspect of the climate modelling community, and also provides a basis for estimating uncertainty in future climate change projections at global and regional scales [10].

3.1 Uncertainties in climate projections

The discussion so far in the paper has illustrated three kinds of uncertainties associated with future climate projections. First, is the irreducible uncertainty

associated with the fact that the climate system is chaotic and thus exhibits natural (or internal) variability. Second, is the uncertainty associated with future energy and emissions scenarios (that is, we don't know as a global society when and how we will wean off fossil fuels). Finally, the third uncertainty is related to the response of climate models to a given future emissions scenario (that is the uncertainty due to inter-model spread).

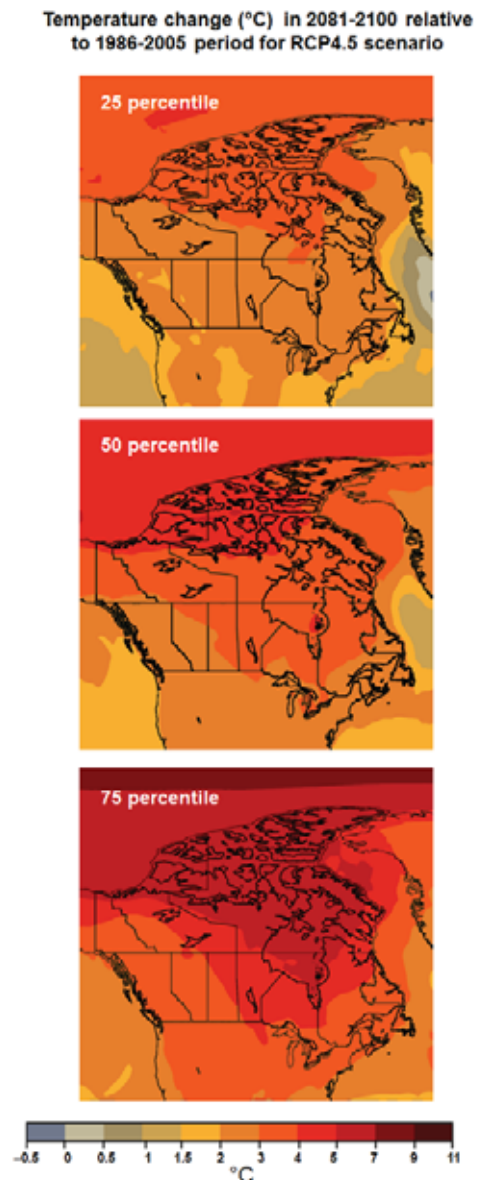


Figure 6: 25th, 50th and 75th percentile values of temperature change over North America for the RCP 4.5 scenario for the 2081-2100 period relative to the 1986-2005 period. The percentile values are based on simulated temperature change from 29 participating models in the CMIP5 intercomparison project. Plots are downloaded from the Canadian climate data and scenarios website <http://climate-scenarios.canada.ca/>.

The relative influence of each of these three sources of uncertainty on future climate projections depends on the variable, spatial scale, and time horizon of interest. For example, uncertainty in daily precipitation projections on small spatial scales for the near future will be dominated by natural variability, whereas projections of global mean temperature for the end of the century will be dominated by future scenario uncertainty. Model biases can have an effect on the first and third sources of uncertainty mentioned above.

In addition, to these three uncertainties there is the fact that models are biased. That is, the models do not simulate the present-day climate perfectly. For instance, most climate models underestimate precipitation over the Amazonian region in South America [10]. Suggestions are made in next few sections how to address these uncertainties and biases.

3.2 How best to use climate change information?

How do we then use climate change information from climate models to make the best decision in the context of climate change?

1. Which future scenario is most plausible?

The challenge in weaning off fossil fuels is most evident in the current trend of fossil fuel emissions, which indicate that CO₂ emissions continue to track the high end of emission scenarios [11]. This is not to say that in future reductions in fossil fuel are not possible. The uncertainty in future in regards to which emissions pathway our society will take implies that at the very least climate change information from at least two to three future scenarios must be taken into account. This will provide a range of expected change for a given climate variable (temperature, precipitation, or something else) for addressing a given impacts and adaptation problem at hand. However, depending on the region and timescale of interest, the contribution of natural variability to this range could be very important.

2. How do we address the uncertainty in results from climate models?

The uncertainty due to inter-model spread amongst climate models is best addressed by not relying on climate change information from one climate model but by combining results from multiple models. Such a multi-model ensemble samples both natural variability and structural model uncertainty. The relative influence of natural variability can be assessed by looking at multiple simulations from a given climate model and forcing scenario. The purpose of this exercise again is to span the range of responses that climate models produce for a given scenario. The Canadian Climate Data and Scenarios website (<http://climate-scenarios.canada.ca/>), for example,

provides results from the 29 participating models in the CMIP5 intercomparison project for North America. This is illustrated in Figure 6 which shows the geographical distribution of 25th, 50th and 75th percentile values of temperature change over North America for the RCP 4.5 scenario for the 2081-2100 period relative to the 1986-2005 period. The 0 and 100 percentile temperature change values will be the smallest and largest, respectively, amongst all the 29 participating models.

At the very least, impacts and adaptation studies should try to bracket the range of responses being studied, for example by using the 25th and 75th percentile values. Potential users of the results should be made aware of the ensemble spread. In an ideal world, results from multiple climate models can be used for a given impacts and adaptation problem at hand to provide an ensemble of projections for the desired response.

3. What about the bias in climate models?

One of the limitations in using climate information from climate and Earth system models is that there are often biases in simulated present-day climate. While some common biases exists in all models (such as the example of systematically low precipitation over the Amazonian region in South America [10] mentioned earlier) in most cases the biases are different in different models. So climate model A may be too warm over North America, climate model B may be too cold over Australia, climate model C may be too wet over the Indian sub-continent, and so on. One way to minimize the effect of biases in simulated present-day climate is to use the multi-model mean together with the 25th and 75th percentile values. In fact, when comparing model results to observations the multi-model mean compares best with observations. Tebaldi and Knutti [9] cite several examples of applications of climate model results to make the case that combined information from several models is superior to results from any single-model.

Other than using results from multiple models, there are also explicit ways to account for bias when using results from a given climate model. The simplest way of addressing bias in climate models is not to use absolute values but rather the change or anomalies relative to the simulated historical mean (for example, as shown in Figures 5-7). The assumption here is that even if the present day climate is not perfectly simulated there is value in the simulated change. This is, for example, done by using absolute change in temperature and by using percentage change in precipitation. More complex statistical bias correction methods are also available that correct systematic errors in model simulations beyond the mean, for example for quantiles of a distribution or even the dependence between variables [12] (Quantiles are values that divide the range of a probability

distribution into intervals with each interval containing the same fraction of total population). Bias correction can be particularly important when considering climate change impacts that depend on the crossing of absolute thresholds. For example, snow accumulation is sensitive to projected temperatures above and below freezing. While these methods can be useful and fit for some purposes, it is important to assess critically whether model biases can be meaningfully corrected [13]. A combination of process insight, model evaluation, and bias correction is needed to inform impacts and adaption decisions [14].

4. I want future climate data for my backyard!

One limitation of global climate models that is perhaps noted the most is their coarse spatial resolution. Despite advances in computing technology the current resolution of most climate models varies from about 100 km to 300 km. This fairly coarse spatial resolution has motivated the development of regional climate models (RCMs) which aim to downscale climate output from global climate models. "Downscaling" refers to deriving high-resolution information from the coarse-resolution information that is available from GCMs. RCMs are based on the same science principles as GCMs but operate over a much smaller domain, a finer spatial resolution, and are driven at their boundaries by data from GCMs. Since RCMs are based on the same physical principles as GCMs, downscaling by RCMs is referred to as "dynamical" downscaling, as distinguished from statistical downscaling that uses different types of mathematical models. The typical resolution of RCMs is about 5 km to 40 km, with some models now reaching resolutions of less than 4 km that can resolve convection rather than parameterizing it (atmospheric convection is a process by which warmer air rises, creating an upward current in the atmosphere). In essence, RCMs attempt to "zoom in" on climate information generated by GCMs.

This is illustrated in Figure 7 which shows simulated changes in precipitation over North America for the period 2081-2100 relative to 1986-2005 for the RCP 4.5 scenario [15]. The results are based on CanESM2 (which is a global Earth system model) and CanRCM4 (Canadian regional climate model). CanRCM4 and CanESM2 are both based on the same physics and CanRCM4 is driven at its boundaries by data from CanESM2. Note how CanRCM4 is able to provide greater detail than CanESM2 because of its finer spatial resolution. While RCMs do provide climate change information at a much finer spatial resolution than GCMs their added value is still debated in the climate community [15], [16]. Note also that in Figure 7 modelled results indicate an increase in precipitation over Canada. The 24-hour extreme precipitation with 10-year return interval is also projected to increase over most of Canada by 10-20% for the period 2081-2100 relative to 1986-2005 (not shown here but see Figure 7 of Scinocca et al. [15]).

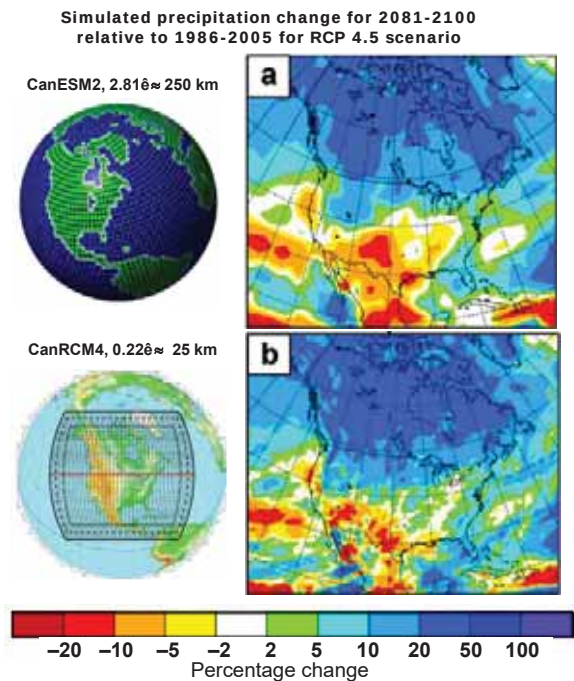


Figure 7: An illustration of dynamical downscaling of climate information by a regional climate model (CanRCM4). CanRCM4 is based on the same physics as its parent global model CanESM2 and is driven by data from CanESM2 at its boundaries. Results and figures are from Scinocca et al. [15].

4. Conclusions

Global climate and Earth system models are the primary, and perhaps the only, viable tool available to us as a society to quantify the possible impact of increases in the atmospheric concentration of GHGs on the changing climate of our planet. While these models have limitations, the core objective of any impacts and adaptation exercise should be to use climate change information from these models in best possible manner. There are three primary caveats associated with climate change information: 1) the future emissions pathway that our global society will take is unknown; 2) for a given future emissions scenario there is uncertainty in projected climate change due to model uncertainty and natural climate variability; and 3) since climate models aren't perfect simulated climate for the present day is biased.

The effect of these caveats is minimized by 1) using climate change anomalies from a given climate model as opposed to absolute values, 2) where it makes sense, further bias correcting climate model output, 3) using climate change information from multiple climate models preferably their multi-model ensemble mean along with the 25th and 75th percentile values, and 4) using results from at least 2 to 3 future climate

scenarios. The objective behind using results from multiple future scenarios and climate models is to obtain an uncertainty range for the response being studied. This allows one to make a climate change impact or adaptation decision in light of the uncertainty.

Several regional climate consortia now process climate change results from coarse resolution global climate models and provide the same information at a much finer resolution over regional scales. Some consortia even perform bias correction before redistributing climate change results. In British Columbia, the Pacific Climate Impacts Consortium (PCIC) is such an organization.

Decision making in light of uncertainty is routine in several aspects of planning. Earthquake preparedness, for example, is based on a highly uncertain low probability but high-impact event. Adjustments to interest rates are routinely announced by federal banks despite uncertainties in future economic outlooks. Decision making in context of climate change adaptation should likely be no different.

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Challenges and potential solutions for the resilience of multi-infrastructure systems

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Abstract:

Resilience, referred to here using two common definitions from the literature – the ability of a system to achieve a desired state within an acceptable time following a disturbance and the ability of a system to change gracefully to a desirable state as a result of a previously unaccounted for event - captures both epistemologies of risk – the manageable and the unknowable – and emphasizes the crucial role of an appropriate system response in recovering, surviving and flourishing in a risky world. There are many challenges, however, in the application of resilience – especially to large multi-infrastructure systems, such as those found in cities. A scan of the literature reveals that the difficulties include, at a minimum, (1) the market failure for data on multi-infrastructure systems, (2) the relative lack in the understanding of the latter definition of resilience – graceful extensibility – in multi-infrastructure systems; and (3) the absence of benchmarks. The Resilience Assessment Platform, useful for building resilience models of multi-infrastructure systems that can be analyzed using the Graph Model for Operational Resilience is used here to demonstrate these challenges and to point to potential solutions with respect to resilience to shocks. The illustration shows how the impact of the market failure can be quantified and how game theoretic approaches could be applied to address the lack of participatory information sharing. Further, red teaming in combination with the Resilience Assessment Platform is suggested as a means for examining graceful extensibility of multi-infrastructure systems. Finally, addressing the market failure and the need for more study of graceful extensibility is suggested as a means to resolve the challenge of creating benchmarks from historical events.

Keywords:

resilience, graceful extensibility, multi-infrastructure, resilience assessment platform, graph model for operational resilience

1. Introduction

Multi-infrastructure systems underpin the functioning of our society. There is scarcely an example in a modern economy of one type of infrastructure operating independently from all other types [1]. The coupling of different types of infrastructure, furthermore, is increasing as communications (i.e. 'smart') technologies find increasing use in advancing the efficient and effective operation of infrastructure.

While the benefits of infrastructure interrelationships accrue, so do the detractors. For instance, when one infrastructure ceases to operate, there is often a cascade of failure across different infrastructure [2]. Further, because coupling is also increasing due to tighter co-location of infrastructure in dense urban areas, the failure effects of one infrastructure, such as a fire, can create a failure in nearby components of other systems [3].

Conventionally an approach for managing these challenges involves assessing how failures occur and cascade and making efforts towards prevention [2]. An emerging modification of this approach – a *resilience* approach – aims to balance prevention with an accelerated recovery of functioning [4], [5]. Resilience recognizes that some failure is unavoidable in large systems and that many impacts of failure occur when recovery is slow or non-existent [6].

The objective in this paper is identification and

advancement towards addressing three major issues in the resilience of multi-infrastructure systems. These challenges are the issue of the inadequacy of available data; the resilience to 'unknowable' risks; and the lack of benchmarks or standards.

2. Resilience Challenges

The first issue is the challenge in accessing the necessary data to understand the interrelationships of infrastructure. This arises because infrastructure is often owned, operated and used by a variety of different stakeholders [7]. Common reasons for not sharing the data include, concerns that out-of-date data will be used for future study or that competitive advantages or weaknesses will be exposed.

The second issue arises, in part, because of the very need for a resilience approach. Within the epistemology of risk there is the perspective that it can be managed [8] and the perspective that there is always unknowable risks with potentially outsized impacts [9]. Resilience practices acknowledge both of these perspectives by offering an advanced means to manage 'knowable' risk and by providing a means to study the ability of systems to extend gracefully when the truly unexpected occurs [10]. This latter issue of understanding the potential for graceful extensibility is the second issue addressed.

The third issues is the absence of benchmarks in the field of resilience. Benchmarks find successful application in prevention, particularly at the individual component level, in the form of performance based codes and standards. For individual infrastructure systems there are emerging standards (e.g., [11]), though they typically miss the recovery aspects of resilience, and the topic of graceful extensibility. For multi-infrastructure systems resilience, there is yet a standard.

3. An integrated proposal

The proposed mechanism for addressing these challenges focusses on an integrated proposal comprised of an iterative set of steps as shown in Fig 1.

First, since the interrelationships in multi-infrastructure systems are most evident when they fail in crises, it is recommended that the process of data collection during such events is revised to record, in a tabular form, the nature of multi-infrastructure failures, and their processes of recovery. At a minimum this must detail the causal chain and timing of events, the other interacting entities, such as supporting operations, and the timing of events. Presently when this information is recorded it tends to be at a coarse resolution and in a non-standard and non-machine readable format making further study difficult.

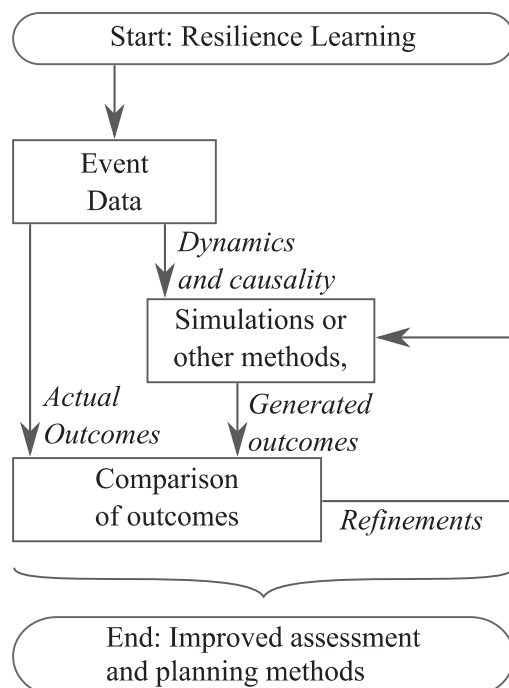


Fig 1: Schematic of integrated proposal for addressing resilience challenges

Once collected this data can be used in planning and simulation in order to improve system resilience

and to hone simulations and provide a base quantity of test cases upon which the simulations can be compared. Here the intention is to extract evidence to inform standards while creating simulation benchmarks.

Finally, validated simulators can be used to test multi-infrastructure system response to 'unknowable' risks. This can be accomplished by progressively increasing and randomizing the severity of initiating hazard effects on multi-infrastructure system models. This effectively follows the patterns of computational red-teaming where computerized representations of complex systems are stressed by an outside agent (the red team) to uncover unconventional vulnerabilities [12].

This final stage provides a formalized means to commence a practice of assessing the ability of systems to extend gracefully. This is proposed as an essential next step, but is likely one of many to follow as this concept is researched further. It is likely that some properties of multi-infrastructure systems may only be uncovered when the actual 'unknowable' events occur. In such instances, however, this proposal comes full circle as the data collected from those events can be collected and fed into the simulations in future iterations so that the learning is not lost.

4. Results and discussions

The Resilience Assessment Platform can be used to illustrate an implementation of the method. The Resilience Assessment Platform (RAP) is a suite of capabilities for ingesting data, converting that data into models that can be used to estimate the cascade of effect and the dynamics of recovery and to assess the impact of potential interventions. It is built on the Graph Model for Operational Resilience (GMOR), which provides the core simulation capability [5]. Under this approach, models are constructed using a description of entity dependency relationships for nominal functioning and for recovery as described in Table 1.

Schematic 9 in the table represents the repeated module for representing an infrastructure, operational or human component within a larger system. This module can also be adapted to include different failure modes and different recovery requirements. The recovery requirements link a component to others in the system. In so doing it is possible to build a depiction of a larger system.

In applying the proposed framework the data collected from events can be combined with the other data sources used in RAP, such as Geographic Information Systems depictions of infrastructure. The data collected from events can refine the recovery requirements and the timing parameters in order to improve the depiction and resulting simulation in GMOR of a multi-infrastructure system.

Further, RAP can be used to simulate different foreseen and unforeseen scenarios to assess graceful extensibility.

Table 1: Model specification for RAP's use of GMOR.

Id	Model Schematic	Description						
1		Entities have timing parameters (τ) that dictate when their state changes once their dependency requirements are met. Entity states are either 1 (i.e., working, available, functional, present, etc.) or 0 (otherwise).						
2		This is a basic dependency requirement. If Entity B is in state 0 then so is A (the state of B is determined by the states of its dependences - not pictured). If the state of B switches from 1 to 0, the state of A changes immediately. If the state of B changes from 0 to 1 it takes τ_A units of time for A to change state.						
3		The outward state of A is dependent on an internal state (S_B). An internal state is only ever set during initialization of a model (i.e., it is an initial condition).						
4		Entity A is in state 1 if both B and C are in state 1.						
5		Implies AND (see schematic 4).						
6		Entity A is in state 1 if B or C are in state 1.						
7		Entity A is in state 1 if B is in state 0.						
8	<table><tr><th colspan="2">Function Name</th></tr><tr><td>$\tau_R=0$</td><td>$\tau_T=1.0$</td></tr><tr><td>$s_{Fail}, \tau_{Fail}=-1$</td><td>$\tau_F=0$</td></tr></table>	Function Name		$\tau_R=0$	$\tau_T=1.0$	$s_{Fail}, \tau_{Fail}=-1$	$\tau_F=0$	This is the most commonly repeated architecture. If at time zero there is no failure the function is in tact. If there is a failure at time zero then the function will recovery in one unit of time (assuming the requirements for the recovery entity are in state one at time zero – this would be determined by this entities dependencies which are not pictured). For entities that represent occurrences of failures it is common to specific a τ of -1. This means the simulation engine will never change the state of this entity. This allows failure entity internal states to act as initial conditions. The timing parameters for the other entities is typically anything greater than or equal to 0. Event types are shown in <i>italics</i> , the requirements for the recovery entity will typically depend on a variety of function, system, and resource entities.
Function Name								
$\tau_R=0$	$\tau_T=1.0$							
$s_{Fail}, \tau_{Fail}=-1$	$\tau_F=0$							
9		Any entity can depend on a resource and multiple entities can depend on the same resource. A resource has a limit (r) that it can supply at any one time. Entities that depend on a resource place a demand (d) on the resource. This demand is applied during state changes of the entity from 0 to 1. If multiple entities require a resource at one time then the state changes of those entities have to occur in sequence. This order can be specified or randomized.						

5. Conclusions and outlook

As disaster losses continue to mount globally action is progressing on many fronts, aided by such things as the United Nations Sendai Framework on Disaster Risk Reduction. Despite the progress there remain pressing difficulties. This paper unites three common challenges of resilience planning in multi-infrastructure systems. These challenges include acquiring data; understanding system response to unpredictable stimuli; and the need for benchmarks. The proposed solution to advance the practice of resilience professionals involves a long-term and united effort to create an iterative and far reaching learning program that can also be used to vet methods of assessment and simulation. It is hoped that such a program can motivate coordinated action for learning on the growing scale and importance of complex multi-faceted systems, such as the infrastructure upon which we all rely on a daily basis.

Looking to future work it is expected that this approach will also apply to domains beyond multi-infrastructure systems, such as buildings. The same trends in system interrelationships that is occurring in infrastructure is also increasingly the case in modern buildings [14], [15] and in large internet and cloud services, for instance.

Much work remains to produce a detailed specification of the data requirements that RAP and other methods, or future methods might require and to formalize a means to update today's data collection practices.

Acknowledgements

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A New Era of Energy Codes in Canada

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Abstract:

As local, provincial and federal governments commit to deep greenhouse gas reductions, building energy codes are adapting to support these outcomes. In addition to greenhouse gas reductions, developing durable, comfortable and resilient buildings are also priorities for jurisdictions. Critical to the development of these new energy codes is identifying the appropriate metrics and administrative requirements to achieve all the desired objectives. Using the City of Toronto's Zero Emissions Building Framework and the City of Vancouver's Zero Emissions Building Plan as examples, this paper will show how a combination of global best practices research, big data analysis, and stakeholder engagement can lead to robust energy policy over the long term.

Keywords:

Zero Emissions; Net Zero; Energy Code; Energy Policy; Thermal Bridging.

1. Introduction

Countries and local governments across the world have begun to make serious commitments to reducing their greenhouse gas (GHG) emissions. As a part of its obligations under the Paris Agreement, the Canadian government has committed to reducing the country's annual GHG emissions by 30% below 2005 levels by 2030. Canadian provinces and cities are following suit, setting emissions reduction targets across their jurisdictions, as well as in particular sectors. As buildings accounted for approximately 87 megatonnes of the GHG emissions released in Canada in 2014, the buildings sector plays a key role in achieving these targets.

A principal means that provinces and some cities are using to reduce emissions from new construction is through the release of new building codes that require significant energy use and emissions reductions over time. Two such jurisdictions are the cities of Toronto and Vancouver – two very different cities with respect to their control over the building design and construction industry. Both cities have recently released zero emissions building plans that lay out a framework and roadmap to reducing emissions from new Part 3 code-compliant buildings to zero by 2030. Using these two plans as examples, this paper will show how a combination of global best practices research, big data analysis, and stakeholder engagement can lead to the development of robust building energy policy. We explain the key elements and processes that were critical to the development and eventual adoption of these new municipal energy codes, including the need to identify the appropriate metrics and administrative requirements to achieve all the desired objectives.

We begin in Section 2 by explaining the need for a new approach to building codes that specifically target

greenhouse gas reductions, followed by an overview of the our two case study cities, Toronto and Vancouver, in Section 3. In Section 4, we present the steps that were taken to develop both cities' plans, noting the importance of stakeholder engagement and capacity building to the process. In Section 5, we conclude with a summary of our experience in following these steps, and provide recommendations for the development of future building codes intended to reduce GHG emissions.

2. Why do we need a new kind of building code?

Jurisdictions across North America often have multiple goals where the built environment is concerned. As noted in the introduction, many local governments seek reliable, long-term emissions reductions from their building stock in order to meet their broader emissions reduction targets. These goals intersect with others, both traditional (e.g. ensuring improved building durability) and less precedence (e.g. improving resilience to increasingly unpredictable climates and extreme weather events). These are joined by still other requirements, such as the need to continuously update code requirements in a way that that is both predictable and achievable by industry, and enforceable by code officials.

However, despite increasing improvements to our building codes, several of these outcomes are not being achieved. North American building codes face several key issues in the achievement of their desired outcomes; of these, three are of particular interest here. First, the metrics that building codes use to assess building performance focus on relative energy or energy cost performance, which may not directly correlate to absolute GHG emission reductions. Second, current building codes allow the use of technological improvements to lighting and HVAC

systems to compensate for poor building enclosures. This practice can lead to the construction of buildings that cannot realize energy savings without the implementation of extensive and sophisticated operations and maintenance programs. Finally, frequent changes and updates to the building code are both difficult for the building industry to manage, and furthermore do not readily translate into measurable performance improvements, at least not without the use of detailed studies that give overall context to the multitude of individual clause changes in the code.

The reason for these limitations is rooted in the structure of our base building codes. ASHRAE 90.1, the predominant building energy code used in North America, and the Canadian National Energy Code for Buildings (NECB), are both based on a detailed set of prescriptive requirements for building components that contribute to energy performance. These are typically broken down into categories of building envelope, HVAC, Service Water Heating, Lighting, and other electrical systems (e.g. motors). While building designers can simply meet these prescriptive requirements, compliance can sometimes be achieved using other methods. One such method is through the use of a tradeoff, in which performance thresholds in one component are relaxed in exchange for higher performance in others, within the same overall category (e.g. building envelope). Another alternative to compliance is achieved through an assessment of whole building performance, in which compliance is assessed on annual building energy or energy cost in comparison to a fictitious "reference building". Reference buildings have the same general physical and operating characteristics of the design building, but are set up in such a way that they meet all minimum code requirements.

Despite this flexibility, both ASHRAE 90.1 and NECB also contain fixed parameters for which building designs do not get full credit (e.g. building orientation, airtightness), despite their potential impact on building energy performance. They are also subject to changing parameters that may influence the relative performance of a design disproportionately to its absolute performance. For example, the use of higher efficiency technologies such as heat pumps in building design means the reference building may also use heat pumps, thereby eliminating the benefit of using heat pumps in relative code performance terms. Moreover, each code focuses on a single metric, despite the existence of multiple desired outcomes. For example, ASHRAE 90.1 bases compliance on energy cost. As electricity currently costs more than natural gas, this approach places significantly more emphasis on electrical savings than on fossil fuel savings. The result is the discouragement of GHG reductions in Canadian provinces where electricity is both the most expensive and cleanest fuel source (e.g. British Columbia). These and other potential discrepancies between

outcomes are shown in Table 1, which explores the relative savings in energy cost, GHG emissions, and energy use between different building scenarios.

Table 1: Differences in relative savings for multiple metrics and grid emissions intensity

Building Scenario*	Relative Savings Over Base Code		
	Cost	GHG	Energy
<i>Natural gas savings only, high carbon grid</i>	11%	9%	25%
<i>Electrical savings only, low carbon grid</i>	38%	40%	25%
<i>Natural gas savings only, low carbon grid</i>	11%	40%	25%
<i>Electrical savings only, high carbon grid</i>	38%	10%	25%
<i>No Savings, 100% electric building, zero carbon grid</i>	-50%	100%	0%

*Data assumes a base building with 50% split of gas and electricity. GHG emissions intensities are assumed as Natural gas: 180 gCO₂/kWh; 40 gCO₂/kWh for "low carbon grid"; 800 gCO₂/kWh for "high carbon grid".

3. Crafting new codes: Toronto and Vancouver

For the reasons noted above and others, several jurisdictions have begun to explore alternatives to the basic building code that are better equipped to meet their emissions reduction and other goals. Two such jurisdictions represent two of Canada's major urban centres: Vancouver and Toronto. These cities share some key similarities: both cities have committed to reducing their emissions by 80% over 1990 levels by the year 2050, and have turned their attention to the buildings sector as a means of doing so. Both cities have a large and growing demand for new residential and non-residential spaces, which already contribute approximately 56% of Vancouver's total emissions, and 48% of Toronto's. Both cities are also focused on reducing building emissions in the key building archetypes that are experiencing the highest growth: low- and high-rise multi-unit residential buildings (MURB), commercial office buildings, and commercial retail, which together make up between 85% and 90% of new construction in both cities.

However, these two cities also have several unique characteristics that distinguish them. Some of these key differences include the following:

- *Climate:* While Toronto experiences hotter summers and colder winters in Climate Zone 6, Vancouver enjoys a milder climate in Climate Zone 4.

- **Regulatory Power:** Toronto is required to conform to the Ontario Building Code and enforces building performance at Site Plan Assessment. Vancouver enforces building performance via the City's own building code.
- **Grid Emissions Intensity:** Toronto's grid power is derived from a mix of nuclear, natural gas, hydro, wind, resulting in an average grid intensity of 50g CO₂/kWh. Vancouver's Grid power is derived primarily from hydroelectric dams, resulting in an average emissions intensity of 11g CO₂/kWh.

Despite some of these differences, the processes used to create their individual zero emissions building plans shared considerable similarities. In the following sections, we present the key steps that were taken to successfully create each city's plan.

4. Identify Objectives and Outcomes

A first and important step in the creation of any city plan is the establishment of clear objectives and intended outcomes that the plan will be designed to achieve. Both Toronto and Vancouver expressed an interest in achieving significant emissions reduction outcomes in line with their stated intention to reduce citywide emissions by 80% by 2050. As such, the focus of both plans was not only on energy use reductions, but on the reduction of emissions specifically. Each city also had additional goals and criteria to be met alongside these emissions reductions. In Vancouver, there was an emphasis on creating what was termed an "envelope first" approach, which had the goal of ensuring that any strategies a designer might employ to reduce building emissions would necessarily target improvements in building envelope performance prior to any mechanical upgrades or renewable energy generation. This approach was later adopted in the development of the City of Toronto's plan as well. In this case, the emphasis was placed on achieving a combination of multiple goals: reducing GHG emissions, increasing energy efficiency, and improving building resilience to the impacts of climate change, including power outages, extreme heat events, and flooding events.

5. Explore Best Practices

Once the key goals of each city were established, the next step in our process was to explore existing research and practice to identify lessons learned in the development and application of codes and standards with similar goals. This review included a comprehensive assessment of global best practices in energy efficiency conducted in 2015, which explored 12 voluntary and mandatory approaches to improving building energy performance in North America and Europe. This research revealed a number of findings related to the success of the reviewed approaches in achieving actual energy and emissions reductions. The full set of findings and recommendations can be

found in the final report prepared for the City of Toronto; however, key findings included the following:

- **Performance targets** approaches (vs. prescriptive approaches) that establish performance targets for energy use intensity (EUI) are successful in reducing building energy use while maintaining the potential for creativity in their achievement, as well as relative simplicity in ensuring compliance.
- The establishment of a **thermal energy demand intensity** (TEDI) target alongside total energy use intensity (TEUI) incentivizes a focus on higher performance building envelopes, which improve building resilience and lower maintenance costs over time.
- The establishment of a **greenhouse gas intensity** (GHGI) target is necessary to ensure actual emissions reductions by requiring designers to focus on the emissions intensity of the fuel source.
- **Mandatory prescriptive measures**, such as requirements for submetering, commissioning, and airtightness testing, help to ensure the actual achievement of modelled building performance.
- The establishment of a **long-term target** (e.g. net zero) and target date (e.g. 2030) helps to provide the building industry with consistency, predictability, and drive innovation.

These and other findings were then used as a basis to compare the current codes in use by both Toronto and Vancouver. The results of this comparison are presented in Table 2, which shows that absolute performance levels of typically code compliant buildings are significantly higher than the absolute performance demanded by some of the leading high performance standards identified in the global best practices research (in this case, Passive House). Target-based approaches, including those used in Passive House, were a common feature among higher performance standards, rather than the reference based or prescriptive based approaches used in current North American building codes.

6. Identify Metrics and Thresholds

The results of this assessment led to the selection of a performance targets for as the basis for both city codes. It was then important to identify an appropriate set of targets for different building types. In both cities, multi-unit residential buildings make up 70-80% of development, with commercial and retail buildings making up an additional 10-15%. These three building types were therefore the focus of further analysis, which centred on answering the following key questions:

- How does current construction practice perform with respect to the key metrics (TEUI, TEDI, GHGI) identified in the review of global best practices?
- What energy efficiency measures are needed to achieve the desired outcomes and what do they cost?

- What metrics are ideal for tracking the city's desired outcomes, and what performance levels are required today and into the future to meet their emissions reduction and other goals?
- Table 2: Building scenarios and their implications for energy savings, TEDI, EUI and GHGI

Sample Scenarios from Analysis	TEDI (kWh/m ²)	TEUI (kWh/m ²)	GHGI (kgCO ₂ /m ²)
1. Toronto: Typically Compliant Building Natural gas heating, R4 (ft ² ·F·h/Btu) walls, double-glazed windows, code level of infiltration, heat recovery used on ventilation	77	190	25.7
2. Vancouver: Typically Compliant Building Natural gas heating, R4 (ft ² ·F·h/Btu) walls, double-glazed windows, code level of infiltration, no heat recovery used on ventilation	79	169	21.4
3. Low Energy Building As defined by Passive House Institute	30*	75*	n/a
4. Passive House Certified Building Minimally compliant level as defined by Passive House Institute	15*	60*	n/a

*TEDI and EUI metrics vary by building standard, depending on rules and assumptions of that standard. The TEDI and EUI values noted here from the Passive House Institute would likely result in even lower values if using the same methodology in the Toronto and Vancouver codes.

- What are the risks in using target-based metrics for building characteristics typically controlled for in reference-based approaches (e.g. building geometry, occupancy density)?
- Are there technological or cost barriers to achieving high (i.e. net-zero or near net-zero) levels of performance in the future?

These questions were answered using a large scale form of parametric analysis. Representative archetypes (i.e. generic buildings with typical characteristics in line with the average or common built project) were developed for each building type (MURB, Commercial Office and Retail), which were then modified for various building characteristics. This process generated hundreds of thousands of energy models and corresponding results. Input characteristics represented a range of potential energy efficiency measures and program variations, and included:

- Wall performance (effective wall R-values used in the models account for all heat loss components, which include not only assembly heat loss, but also the heat loss associated with interface details);

- Window performance (from double-glazed to triple glazed);
- Roof performance (effective roof R-values);
- Window to wall ratio (from 20% to 60%);
- Air leakage performance (from 2.0 to 0.1 L/s/m² at 75 Pa);
- Building shape (vertical surface area to floor area ranging from 50% to 100%);
- Occupancy density (from single room occupancy MURBs to large, luxury suites);
- Mechanical system fuel type, and equipment type/efficiency (e.g. boilers, heat pumps);
- Service water heating savings through the use of low flow fixtures and drainwater heat recovery; and
- Lighting power density reductions.

Output metrics extracted for each of the models included energy use intensity (TEUI), thermal energy demand intensity (TEDI), greenhouse gas emissions intensity (GHGI), incremental capital costs, net present value, energy and energy cost savings relative to the current building code.

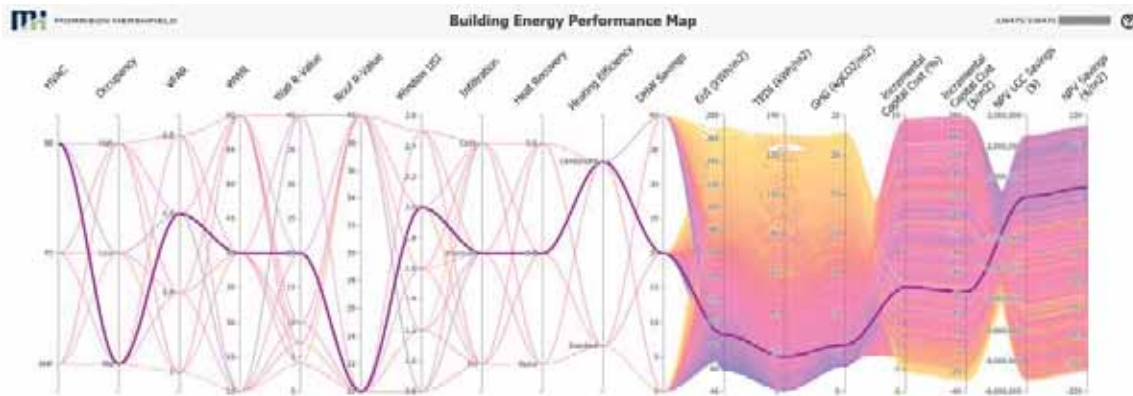


Figure 1: Screenshot of the Building PathFinder tool

Table 3: Building Scenarios and their implications for energy savings (TEDl, EUl, and GHG)

Sample Scenarios from Analysis	Energy Savings from Code (%)	TEDI (kWh/m ²)	TEUI (kWh/m ²)	GHGI (kgCO ₂ /m ²)
1. Vancouver Code-Compliant Building - NG Natural gas heating, R4* effective walls, double-glazed windows, code level of infiltration, heat recovery ventilation	0%	50	148	15
2. Vancouver Code-Compliant Building – Elec Electric heating, R4* effective walls, double-glazed windows, code level of infiltration, heat recovery ventilation	0%	43	130	1.4
3. Scenario 2 with High Performance Envelope R10* effective walls, triple glazing, air-tight envelope	32%	12	90	1.0
4. Scenario 3 with Large Surface Area 50% more surface area to volume ratio	31%	26	104	1.1

*Effective wall R-values in ft²·F·h/Btu inclusive of all opaque heat loss elements, including assemblies and interface details. Values for typical construction are R4, improved at R10 and high performance at R20 for high-rise MURBs¹.

Building PathFinder, a tool based on a multi-variable visualization technique called parallel coordinates, was used to analyze the data for trends and patterns (Figure 1). The results of the analysis confirmed the need to set metrics that directly measure specific outcomes. A sample of data derived from the City of Vancouver's analysis are presented in Table 3, which show the impact of different fuel types (natural gas vs. electricity), high performance envelopes, and building shape on building energy and emissions performance.

Key findings from the data included the following:

- Energy efficiency alone may not achieve the desired GHG emissions reductions. Having a GHGI reduction target explicitly influences the types of fuel that may be used on a project (See Scenarios 1 and 2 in Table 3).
- TEDI is a good metric for minimizing heating loads, ensuring good and more durable building envelopes and efficient ventilation systems (See Scenarios 2 and 3 in Table 3, which show similar GHG outcomes, but very different TEDI values).
- Energy efficiency measures not typically addressed by current codes can have a significant impact on

performance (See Scenario 3 and 4 in Table 3, where increased surface area for the same design characteristics leads to much higher TEDI).

- A low TEDI value corresponds well with passive survivability, represented by the interior zone temperature during a 2 week, winter power outage. For example, a code compliant building in Toronto with a poor building envelope will drop to -6°C at a TEDI of 80 kWh/m²/year compared to a Tier 4 compliant building under the new Zero Emissions Building Framework, which will only drop to 7°C at a TEDI of 10 kWh/m²/year).

7. Set targets

Once an understanding of the key metrics and basic outcomes of different combinations of energy conservation measures was understood, a process of stakeholder consultation was held with members from the local building industry to set appropriate targets. Series of workshops were held to identify locally available technologies and construction methods, discuss potential cost increases and their palatability with the local industry, and obtain consensus on the

feasibility of a long-term, near-zero emissions target for the end year of 2030. This end goal year was used to derive a number of steps between the requirements of a current code-compliant building, and a near-zero emissions level of performance for each of the metrics identified (TEUI, TEDI and GHGI). Each step was crafted to ensure incremental improvements would be taken over the course of typical 3-5 year code cycle, ultimately leading to the final zero-emissions goal. At each incremental step, the energy analysis data was used to identify the lowest cost solutions that could achieve each step for each archetype. Figure 2 shows the relationship between incremental capital cost (ICC) for MURBs and the trajectory towards zero emissions from the current code in both Toronto and Vancouver.

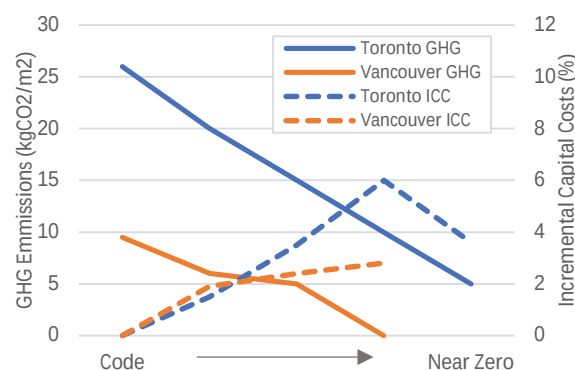


Fig 2: GHG and ICC evolution over time for MURBS

8. Ensure building performance

The findings of the review of best practices in energy and emissions codes from across the world revealed that while performance targets approaches have had the most success in eliciting higher building performance, they are often accompanied by a set of prescriptive requirements. As noted above, these are often included to ensure modelled building performance is actually achieved. These requirements were derived for both cities via combination of best practice research and stakeholder engagement to confirm that they would both help to realize the city's goals and be feasible in the context of the local industry. In the case of Toronto, these included the following:

- **Renewable energy generation:** buildings are either required to be "solar-ready", or to ensure that 5% of their total energy load is supplied by on-site renewable energy systems (or 20% if using geoexchange);
- **District energy connection:** buildings are either required to be district energy-ready (Tier 1) or to connect to a district energy system where one is available (Tier 2);
- **Airtightness testing:** proponents are required to submit an airtightness testing plan at site plan assessment, and the final results at occupancy;

- **Building commissioning:** buildings are required to undergo commissioning, based on the LEED v4 Enhance Commissioning credit
- **Submetering:** buildings are required to have submeters installed by floor/defined use (Tier 1), or by tenant/suite (Tier 2);
- **Energy benchmarking and disclosure:** proponents are required to demonstrate proof that the building has been registered with Energy Star's Portfolio Manager to allow for easy benchmarking later on.

9. Provide Resources

As a final step, both cities required a set of resources that would help both administrators and industry members to comply with the new code. As the shift to a performance targets approach requires new approaches to energy modelling, a set of energy modeling guidelines was created to help ensure clarity and consistency in modelling across all new building applications. The City of Vancouver has also been active in supporting the creation of additional resources that will help improve compliance and ultimately, the success of their Zero Emissions Building Plan. These include guides for improving airtightness, preventing thermal bridging, and others. Tools such as the Building PathFinder² are also available online to help designers explore the impact of different energy conservation measures on building performance.

10. Conclusions and outlook

The process outlined above was carried out successfully in both cities over the course of 2016 and 2017, with the resulting zero emissions building plans approved by both city councils. The City of Toronto has estimated that the framework will result in a reduction in GHG emissions by approximately 30.6 megatonnes by the year 2050, while the City of Vancouver is targeting zero emissions in all new buildings by 2030.

Establishing absolute targets for context appropriate metrics are expected to be more reliable for achieving desired outcomes, specifically to establish building-specific GHG emission targets for cities wishing to meet climate change targets. Even without new technologies that are likely to be available, aggressive building targets have shown to have a minor impact on incremental capital cost and suggest that quicker code iterations or jumping directly to near zero or zero emissions building sooner may be justified.

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¹ <https://buildingpathfinder.com>

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Sustainability through the World's Cities

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Abstract:

Through a systems approach to cities early glimpses of sustainability emerge. Key attributes of an urban systems approach include integration of the scaling law and application of concepts such as urban metabolism, biomimicry and hierarchies. A handful of strategic cities (sufficiently large and well connected) within a country, or globally, could shift the overall socio-economy toward sustainability. Key challenges to achieving this greater sustainability include the need to continually accelerate innovation (the pace of urban growth may overwhelm urban practitioners and citizens); and the need for governance structures that foster alignment of a city-region's objectives locally, regionally, nationally and internationally. Engineers can play an important role in identifying, quantifying and helping to remove these two roadblocks on the path to sustainability. The role that Canada's largest cities might play in advancing sustainability is briefly highlighted.

Keywords:

Urban systems, sustainable cities, sustainability, sustainable urban development.

1. Introduction

Today's structure of nation-states traces back largely to the 1648 *Treaty of Westphalia* that replaced earlier city-partnerships such as the Hanseatic League of Cities. More recently, the global pattern of nation-states fractured extensively: e.g. from 1900 to 2000, the number of countries in the world quadrupled (~196 today, plus territories). Concomitantly with the strengthening geo-political emphasis on nation-states, the latter half of the 20th century saw the *Great Acceleration* where wealth and material flows grew exponentially (anchored in cities). From 1700 to 1800 there was one city above 1 Mn (Beijing). In 1900 only London was larger than 1 Mn, yet by 2000 there were more than 350 cities above 1 Mn population; a number likely to swell to 1000 cities by 2100 (Table 1). Energy and material flows for this massive urban expansion are staggering.

An ephemeral glimpse of sustainability for humanity is possible, and from that, the designs of sustainable development emerge. Population peaks and timing, and corresponding environmental impacts (e.g. peak carbon, waste and biodiversity loss), are projected under various shared socio-economic pathways. In all scenario pathways, the influence of cities rises dramatically this century.

Global sustainability requires sustainable cities, especially the larger world cities (Table 1). Sustainable cities are typified by nurturing environments; adherence to concepts such as biomimicry and hierarchies, systems approach and city scaling; providing a way for citizens (local and global) to live within planetary boundaries while striving for objectives such as the Sustainable Development Goals (SDGs).

2. Power Tools: City Building & Intervention

Through the flow of energy and materials, the emergence of scaling laws in inanimate (geophysical) systems is the same phenomenon as the emergence of allometric laws in animate (biological) systems (aka 'the constructal law') [1, 2].

Urban systems follow the power law (Eq 1), whereby a doubling of city population can lead to more than a doubling of social interaction and economic output with less than twice the demand for new infrastructure. Larger cities can provide more wealth for less (infrastructure) cost.

$$Y(t) = Y_0 N(t)^\beta \quad (\text{Eq. 1})$$

In Equation 1 $Y(t)$ and $N(t)$ represent the urban indicator and city population at time t respectively, and $Y_0(t)$ is a time-dependent constant. β is the scaling component. Considerable empirical evidence illustrates that when city populations double β is ~1.15 (superlinear) for social interaction outcomes, e.g. economy and patents; and β is ~0.85 (sublinear) for inanimate infrastructure, e.g. road surfaces and length of transmission piping [3, 4].

In addition to benefitting from scaling aspects of larger cities, an urban systems approach is strengthened through the application of tools such as urban metabolism, hierarchies, and biomimicry, i.e. borrowing from nature as a way to build and manage cities.

The flow of people along a busy city street exhibits an uncanny similarity to flocks of birds or rushing rivers. Tributaries, streams and creeks, growing into strengthening rivers: water (as well as people, blood

through a circulatory system) follows a self-forming hierarchy. Urban life follows a similar pattern of hierarchies and strengthening flows of people, energy, traffic, etc. People in larger cities, for example, walk faster than those in smaller communities [5].

National economies exhibit similar hierarchies where one or two key cities are at the apex of the hierarchy and generate a disproportionate share of the economy (as well as direct and indirect environmental impact). These larger cities will continue to connect globally, and reinforce inherent hierarchies. Canada's three largest cities, for example, are home to more than a third of Canadians, and more than half the country's economy (both are growing shares).

Intervening in Urban Systems

System analyst Donella Meadows proposed leverage points to intervene in a system [6]. These can be adapted to urban systems as follows (as in Meadows' original work these are presented in increasing order of effectiveness):

xii. Constraints, parameters, targets and operating parameters. Metrics are typically well known by citizens but provide little ability to bring about behavioral change.

xi. Buffering capacity and urban resilience. The system's (city's) ability to stabilize and ameliorate potential shocks, perturbations and supply disruption.

x. Built structure and nodes of intersection. 'Lock-in' effects critical, as costs to change significantly higher than 'building it right' initially (with keen emphasis on optimum flow – e.g. people, traffic, energy, water).

ix. Lengths of delay, responsiveness. Time to build can have a significant impact, however often difficult to 'fast-track'.

viii. Strength of negative feedback loops. The use of preventative medicine and maintenance, full-cost accounting, fast-track' construction and 'just-in-time' delivery (self-correcting).

vii. Gains from positive feedback loops. Can lead to unconstrained growth and increased inequality through 'over-heated' economy (self-reinforcing), e.g. nutrient loading in a lake and eutrophication.

vi. Information flows. Better provision of information (timeliness, completeness). Increased accountability.

v. Rules of the system (city). Who makes the rules (e.g. laws, regulations, standards), who enforces them (and how), and what is the mechanism to change the rules.

iv. Ability to self-organize. Society's capacity to innovate and adapt to changing circumstances (and objectives), applied human creativity, ability to surpass system constraints.

iii. Goals of the city. Broad, system level goals such as survival, resilience, differentiation, evolution. [NB City goals usually align with upper-tier governments, however, if not, rationalization of goals and objectives is needed, and selection of paramount goal(s)].

ii. City paradigm. A shared idea (values) in the minds of citizens, e.g. Rousseau's social contract. [NB

Thomas Kuhn's Structure of Scientific (System) Revolutions suggests working with active change agents and more open-minded, middle ground citizens, e.g. abolishing slavery, colonialism].

i. Ability to transcend paradigms. Akin to enlightenment and self-actualization - going beyond challenging fundamental assumptions, into the realm of changing the constructs that fostered the original assumptions. For example. the ability to rise above, and integrate, two (or more) disparate world-views such as First Nations mother earth and capitalist market dominance.

When intervening in a 'system of systems' such as the world's cities, application of hierarchies and targeting key nodes of influence is likely to yield the greatest influence. The emergence of AIDS (through the key node of Kinshasa) and SARS (through Guangdong and Hong Kong) provide compelling examples. Emergence of global sustainability will follow a similar pattern where key global cities (sufficiently large and well connected) will perturb the system and changes will flow (up and down) through the hierarchy.

Civil engineers play a large role in city building, especially in defining and monitoring operating parameters, providing (quality) information, and establishing the rules of the system (e.g. regulations and standards). Perhaps the greatest role is through the application of values-based cost-benefit analysis, and an overarching focus on public safety. Anchoring public safety in sustainability could catalyze the profession's impact.



Fig 1: Biomimicry in cities. 'That which is not good for the hive, cannot be good for the bees.' Marcus Aurelius

3. Challenges Ahead: Urban Systems

At least three major challenges conspire against sustainability through an urban system of systems, i.e. cities bringing about sustainability.

First, expanding urban economies at *superexponential* rates ($\beta \sim 1.15$) requires ever-accelerating innovation and paradigm shifts (Fig 2) [5, 7]. Without innovation system collapse, *singularity* (dashed vertical lines) is inevitable (as open-ended system growth is unsustainable). The shortening of time between innovations will intensify as more and larger cities emerge and place greater demands on planetary

Table 1: The World's Growing Wealth, Health and Cities

Year	GDP (per person)	Population (Mn)		Life Expectancy	Number of Cities (>1 Mn, 5-10 Mn, >10 Mn)
		Global	Urban		
1500	\$130	461	<40	33 years	1, 0, 0
1600	150	554	<50	35	1, 0, 0
1700	170	603	<60	36	1, 0, 0
1800	200	990	<100	40	1, 0, 0
1900	680	1,650	320	48	11, 1, 0
2000	6,500	6,144	2,950	78	350, 31, 19
2100	40,000	10,853	8,686	83	800, 91, 64

Adapted from Hoornweg D (2016) [7] and World Urbanization Prospects. Constant 2016 US\$

systems (the pressure to cross planetary boundaries is at the early phase). Globally, the urbanization process is only about half complete. Canada may be called upon for evidentiary support, as the country is one of the world's first to reach the 50% urban ratio as far back as 1921 [7].

Second, the benefits of scaling in cities (a key tool to reach sustainability) does not apply beyond national borders [8]. When a country's geopolitical objectives do not align with city-needs, frictions within, and across countries intensify. The emergence of city-member groups like C40 is still nascent.

Third, researchers such as van Raan et al find superlinearity with power law exponents of around 1.15 for cities in the Netherlands, but remarkably urban agglomerations (central city and contiguous suburban cities) of the same population size do not perform as well. The limiting effect is even larger for urban areas

(agglomerations plus all socio-economically connected suburban cities) [9]. This suggests that reorganized (consolidated) municipalities perform better at generating gross urban product.

Sancton's discussion in *The Limits of Boundaries* corroborates the challenge of applying city boundaries to a fluid economic and social entity, i.e. a city [10]. Governance (i.e. borders, priorities, and operating parameters) can interfere with a city-region's inherent ability to grow (innovate) and generate urban product (utility). For example, the inability of larger urban centers, especially the Toronto urban region, to take full advantage of urban scaling likely contributes to Ontario and Canada's perennial calls for greater innovation and productivity relative to comparator provinces and countries [11, 12].

4. Results and discussions

The global costs of 'green infrastructure' and attainment of sustainability objectives such as the SDGs is well known [13, 14]. The growth of cities and commensurate wealth generation can readily meet these costs. Even a slight enhancement of urban scaling laws would provide sufficient funds to meet all the world's sustainability objectives.

The breakneck pace of city growth the world is now experiencing (Table 1) should approach a peak later this century. Our ability to cope with the growing demand for energy and materials, and innovation will surely be tested over the next 7 to 10 decades. Intervening in urban systems to nudge them toward sustainability suggests an approach predicated on good quality, accessible data; emphasis on resilience and a city's buffering capacity; and clear articulation of shared values. These values need to be consistent throughout governed jurisdictions.

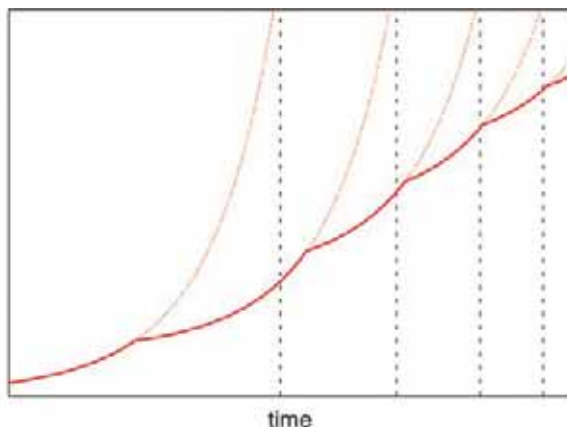


Fig 2: The accelerating pace of innovation in cities [5].

The recent and rapidly intensifying changes to the urban transportation sector are a harbinger. Common aspects of the system-change include: technology may provide 'paradigm shifts', e.g. ride hailing and locational services by phone; vested interests will champion certain approaches (e.g. Uber's lobbying efforts, OEM's reluctance to provide EVs); regulations are a key driver (or hindrance); when services transcend political jurisdictions inefficiencies often emerge; scale benefits are possible (e.g. ReThinkX suggests 50% more mobility at 25% of current costs [15]); integration is critical (with multi-discipline teams); changes are driving major social changes; and, how these changes flow through cities locally and globally is evolving rapidly.

Engineers could help meet sustainability challenges by integrating public safety (values based) with sustainability (longer-term safety). Tools and procedures could be readily developed [7, 16] although governance objectives need to align (locally, regionally, nationally, and internationally). The three most powerful places to intervene in a system are values-based (Sec 2). Cities must align with national and international values – and vice versa.

5. Conclusions and outlook

The economies of scale and efficiencies associated with larger cities are foundational to sustainability. Obstacles on the path include the accelerating imperative for innovation (this will dampen when the overall system approaches steady state and sustainability).

Another key obstacle is governance; how local priorities might be hampered from spreading across the entire urban area, and how overall city objectives may be curtailed from application across the system, minimizing the benefits of hierarchies. City objectives need to be consistent across the full range of their influence and hinterland.

Engineers can play a major role in identifying, quantifying and helping to remove roadblocks to sustainability. In Canada future research is needed on how governance practices may be impacting the pace and depth of innovation. Particular focus is warranted for the three major urban areas, Montreal, Toronto and Vancouver as they contribute disproportionately to the country's economy. Research is also needed to ascertain which urban traits are already scaling globally, and how. Applying this knowledge to other urban functions would likely provide large impetus toward sustainability.

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Cities and Energy Efficiency: Unravelling the Contradictions

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Abstract:

There is still much contention over basic questions surrounding cities and energy efficiency, including if urban living is more energy efficient than rural living and if increasing urbanization helps or hinders efforts to reduce energy consumption. This paper explores these issues by drawing upon key literature and some new results to describe the competing factors that underlay energy use in cities: i) scale effects; ii) wealth effects; iii) density effects; and iv) location-specific effects (such as climate). We conclude that the contradictions may be reconciled by considering cities as dynamic, complex systems that are more energy efficient when it comes to meeting basic needs of individuals, but agglomeration effects of urban economies lead to even greater consumption in the city as a whole.

Keywords:

sustainable cities, energy efficiency, urban scaling

1. Introduction

There is a growing literature on urbanization, the science of cities, and the environmental costs and benefits of an increasing mass of humanity living in cities. Cities are complex evolutionary systems, which we don't fully understand yet. Despite many solid scientific studies, review of the literature reveals there is still much contention over basic questions such as: Is urban living more energy efficient than rural living? Does increasing urbanization help or hinder human efforts to reduce our energy-related environmental footprint on the planet? Towards answering such questions, this paper draws upon key literature—adding a few results of our own—to describe the factors that underlay energy use in cities. We organize the discussion in terms of four factors: i) scale effects (i.e., impact of population size on energy use); ii) wealth effects (including embodied energy); iii) density effects; and iv) location-specific effects (such as climate). We describe how contention arises because there is interplay between these effects; contrary results arise depending on how subsets of cities are chosen and boundaries drawn.

2. Scaling

In the science of cities literature, Bettencourt et al. (2007) have established a variety of scaling relationships for cities. These have shown that social phenomena such as economic activity, patenting and crime scale super-linearly with population size; while length of infrastructure (e.g., road length, cables) scale sub-linearly (Figure 1). Results for energy use in cities are mixed. Household electricity use scales linearly, while total urban electricity use scales super-linearly.

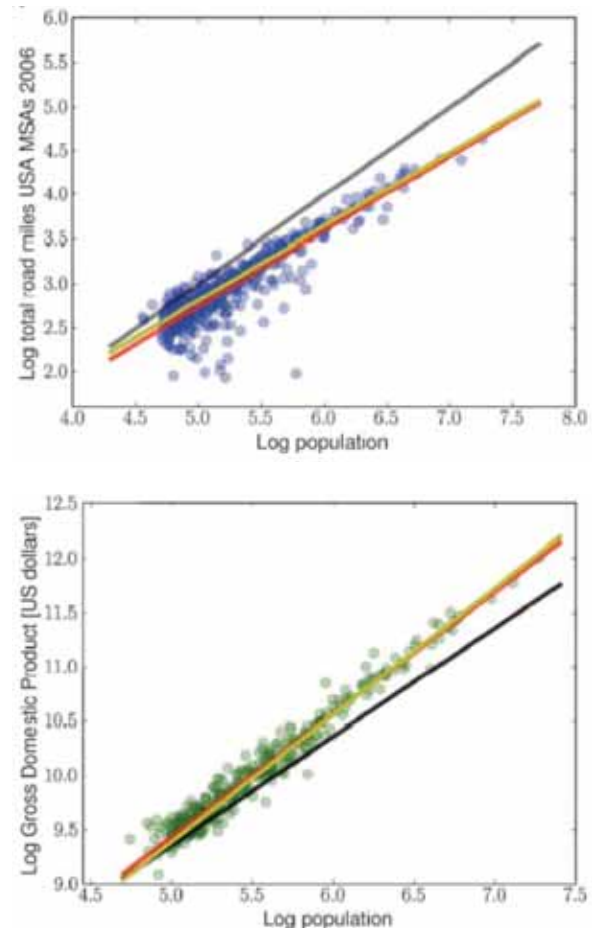


Fig 1: Scaling relationships adapted from Fig. 1 of Bettencourt (2013): length of urban roads in U.S. cities scales sub-linearly (top), while GDP of U.S. cities scales super-linearly (bottom).

A couple of important observations on the scaling relationships should be made:

- i) The relationships only hold when cities in a similar economic or political context are used, e.g., all U.S. cities, or all Chinese cities, but not all global cities.
- ii) The use of log-axes over multiple scales masks a high degree of variation about the trends captured by the scaling relationship. This variation around the trend becomes substantial if cities are considered in a global context, as will be discussed further below.

3. Wealth

The scaling relationships show that as city population increases they become disproportionately wealthier. This can substantially undermine the idea that cities have lower environmental impacts per capita as they become larger. It can be the case, in a given politico-economic context, that larger cities use less direct energy per capita due to density effects, discussed below. The higher rates of personal consumption, however, associated with higher per capita GDP of larger cities likely translates into more energy use and emissions upstream of cities. This is apparent, for example, in the study of U.K. municipalities by Minx et al. (2013) using economic input-output tables.

Looking at a global set of megacities, for which the scaling relationships do not hold, a direct effect of wealth on urban energy use is also evident. Simple (univariate) correlation coefficients between GDP and i) electricity use; and ii) transportation fuel use, are both of the order 0.7 (Table 1). In other words, energy use tends to increase with wealth for global megacities.

Table 1: Simple (univariate) correlation coefficients between urban metabolism parameters and driving factors in a study of the world's 27 megacities (from Kennedy et al, 2015; SI 2).

	Electricity use	Heating/industrial fuel	Transport fuel	Water consumption	Solid waste production	Heating degree-days	Area (km ²) per person	GDP
Electricity use (MWh)	---							
Heating/industrial fuel (GJ)	0.36	---						
Transportation fuel (GJ)	0.58	0.58	---					
Water consumption (kL)	0.52	0.33	0.67	---				
Solid waste production (t)	0.37	0.63	0.30	0.04	---			
Heating degree-days	0.46	0.60	0.54	0.17	0.25	---		
Area (km ²) per person	0.76	0.46	0.75	0.73	0.59	0.42	---	
GDP (\$)	0.69	0.52	0.71	0.48	0.47	0.58	0.80	---

4. Density

For cities in a similar politico-economic context, Bettencourt (2013) has theoretically shown that urbanized area per person scales sub-linearly with city size. The implication of this is that urbanized area

per person scales sub-linearly—a result that we derive and demonstrate empirically elsewhere (Sugar and Kennedy, in progress). The effect of cities becoming denser as they grow lies behind the conception that cities are more energy efficient. The density effect can potentially reduce energy use per capita, a result that is opposite to the wealth effect. Again, however, these results only apply to cities in a similar politico-economic context.

When looking at studies of global cities (Newman and Kenworthy, 1991; Kenworthy et al., 1999; Kennedy et al. 2015), the interplay between wealth effects and density effects is different to the scaling theory. Newman and Kenworthy's inverse correlation between transportation energy use and density (Figure 2); has also been found to apply to electricity use in cities (Figure 3)—because more spread-out cities have greater building space per capita (Kennedy et al., 2015). The dataset of megacities and the older dataset for global cities (Kenworthy et al., 1999) both showed a high correlation between GDP and urbanized area per capita. With the megacities, for example, the correlation coefficient is 0.8 (Table 1). In other words, spread-out cities are wealthier and have higher direct per-capita energy use for transportation and electricity use.

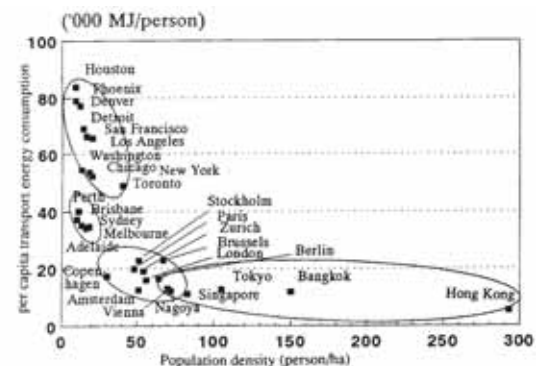


Fig 2: Variation in annual transportation energy consumption and population density between several global cities (Newman and Kenworthy, 1991).

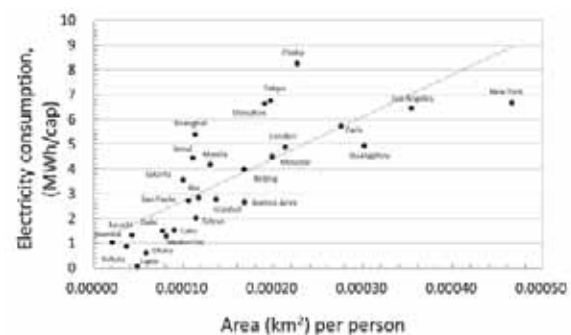


Fig 3: Electricity consumption in megacities is strongly correlated with urbanized area per person (Figure S5 from Kennedy et al., 2015).

5. Location-specific effects

Other factors that impact energy use in cities are location-specific, such as climate and city-specific industrial activities. With respect to climate, per capita energy use for heating and industry (combined) have been found to correlate with heating degree days (Kennedy et al., 2009; Figure 4).

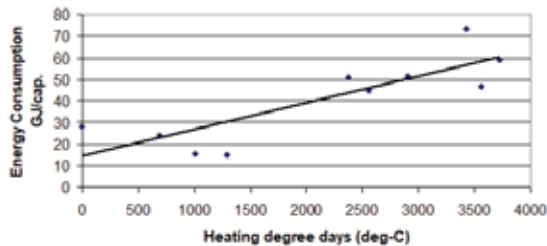


Fig 4: Energy consumption from heating and industrial fuels increases with heating degree days, based on an 18°C base temperature (Figure 2 from Kennedy et al., 2009).

6. Conclusion

In this paper, we explore four key issues surrounding cities and energy efficiency by outlining findings from the literature, as well as results of our own, as summarized in Table 2. From our discussion, we can see that the greatest contradiction concerning urbanization and energy has to do with the conflict between wealth and density effects. On one hand, scaling theory and megacities observations dictate that larger cities are wealthier, and wealthier cities consume more energy. In contrast, larger cities also tend to be denser, which reduces per-capita consumption of transportation and household electricity use.

Table 2: Summary of the four factors underlying energy use in cities.

Factors	Summary
Scaling	Larger cities consume more energy than their smaller cities
Wealth	Larger cities are wealthier than smaller cities; increased wealth leads to increased energy consumption
Density	Larger cities are denser; denser cities consume less energy; spread-out cities are wealthier and have higher energy consumption
Location	Climate and industrial activities impact energy consumption

This main contradiction can perhaps be reconciled by a simple premise: energy consumption in cities must be considered as a dynamic and complex system. Urban living may be more energy efficient when it comes to meeting basic needs of individuals (i.e., density effects); however, the agglomeration effects of urban economies leads to even greater consumption in the city as a whole (i.e., scaling and wealth effects). As cities become more efficient—by building a subway, for example—they transition to a higher order of complexity that drives even more economic activity, consuming more energy and making room for more people, who in turn consume more energy. In this sense, urbanization may not actually help human efforts to reduce our energy-related environmental footprint on the planet. Instead, rapid urbanization requires strategies that can sustain potentially high energy use while reducing adverse impacts, such as a shift to low-carbon energy supplies.

Acknowledgements

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Thermal performance of building frame walls outfitted with encapsulated PCM under full weather conditions

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Abstract:

This paper presents results of the potential thermal enhancements in building walls derived from using phase change materials (PCMs) integrated into such walls. Typical North American construction, namely, frame walls as well as hydrated-salt-based PCM were evaluated in well-controlled test houses under full weather conditions. It was found that PCMs produce reductions in heat transfer rate, both in total heat transfer and peak heat transfer. For the 10% PCM concentration, the largest peak flux reduction of 33.7% was observed when the PCM pipes were installed on the north wall. However, for the 20% PCM concentration, the largest peak flux reduction of 29.2% was found when the PCM pipes were installed on the south wall. The total heat flux was reduced by approximately 27% with 10% PCM concentration and 27.3% with 20% PCM concentration. Doubling the amount of PCM did not produce significant improvement on heat flux reduction. Also, PCMs produced more stable wall temperatures.

Keywords:

Phase change materials, Heat transfer control through building walls, Energy management in buildings, Enhanced building enclosures.

1. Introduction

Evaluation of the thermal performance of building and refrigerated trailer walls outfitted with phase change materials (PCMs) has been conducted since 2000 [1-18]. The purpose of these investigations was to assess peak air conditioning and refrigeration demand reductions, thermal load shift, and energy savings. PCMs work by storing relatively large amounts of heat energy when melting. This heat is released upon solidification of the PCM when the surrounding-to-the-PCM temperatures drop below the PCM solidification point. For building applications, the phase changes are predominantly of the solid-liquid transitions type and PCMs can be organic (e.g., paraffins, waxes, and

oils) or inorganic (e.g., hydrated salts). There also exist PCMs that are mixtures of organic and inorganic compounds and some that are contained within hydrophilic silica powders. Several types of PCMs are shown in Figure 1.

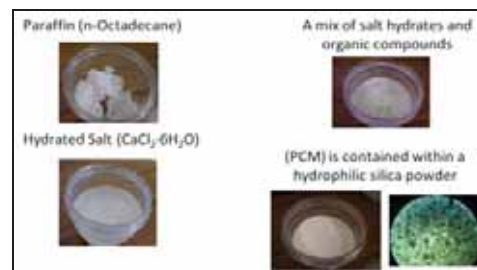


Figure 1. Types of PCMs

In the research presented in this paper, PCMs were integrated into frame walls, a commonly type of walls used in North American residential construction, as shown in Figure 2.



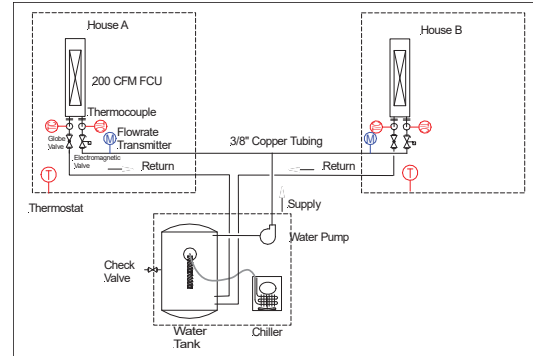
Figure 2. Frame walls

2. Experimental set-ups

The thermal performance of walls outfitted with PCMs was evaluated using two identical $1.83 \text{ m} \times 1.83 \text{ m} \times 1.22 \text{ m}$ test houses (Figure 3a), where one house was used as a control house and the other as an experimental house. The roof was a built-up roof with gray asphalt shingles, 6.8 kg felt, and 1.27 cm plywood sheathing. The wall assemblies were 1.11 cm plywood siding, 5.08 cm $\times$ 10.16 cm studs, and 1.27 cm gypsum wallboard from outside to inside. Insulation (fiberglass and cellulose) with a thermal resistance of $1.94 \text{ m}^2 \cdot \text{K/W}$ (R-11) was used for both the ceiling and the walls. In each test house, a window with an area of 0.32 m^2 was placed in the south-facing walls.



(a) Picture of the test houses



(b) Space cooling system

Figure 3. Control and experimental test houses

For space cooling purposes, a chilled water system (Cooling capacity: 0.4 kW) was designed and field fabricated and installed (Figure 3b). The chilled water system included a water tank, a drop-in coil water chiller, a temperature controller and a set of water pumps. Fan coil units were installed inside each house next to the east-facing walls. The chilled water was circulated from a 265 L insulated plastic water tank to each fan-coil-unit (FCUs) located inside each house. A temperature controller was connected to the chiller to regulate the chilled water temperature in the tank, which was set at around $12.8 \text{ }^{\circ}\text{C} \pm 2.8 \text{ }^{\circ}\text{C}$. The pumps and the electromagnetic valves were controlled by low voltage thermostats to maintain test houses' indoor air temperatures at approximately $21.5^{\circ}\text{C} \pm 0.5^{\circ}\text{C}$. Monitoring systems were installed to measure and collect space cooling loads, wall heat fluxes, air and surface temperatures, and air relative humidity. During the tests, the indoor air temperatures of both houses were well controlled and maintained almost identical to less than 1.5°C difference.

The PCM used in this research was calcium hexahydrate with a melting point of $29 \text{ }^{\circ}\text{C}$ and enthalpy of 131.4 J/g . The PCM was encapsulated in copper pipes (Figure 4), arranged horizontally in the stud walls, and placed next to the interior wallboard. PCM concentrations of 10% and 20% were

investigated. The concentrations were based on the mass of the interior sheathing.

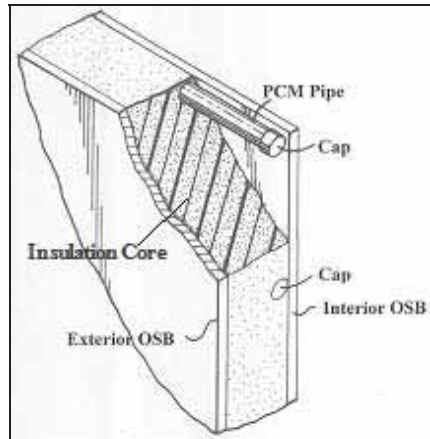


Figure 4. Schematic of PCM encapsulation and installation

Type T thermocouples (T/Cs) were installed to measure indoor and outdoor air and wall surface temperatures. For air temperature measurements, the T/Cs were shielded with aluminum tape to minimize radiation exchange effects. For surface temperatures the T/Cs were covered and painted with a thin film of the same color and texture of the surface whose temperature it measured. Each wall was instrumented with several T/Cs arranged in parallel grids (Figure 5). This arrangement gave a representative wall temperature, which was the average of the measured points. The measuring range and accuracy of the T/C was $-18-93\text{ }^{\circ}\text{C}$ and $\pm 0.6\text{ }^{\circ}\text{C}$. Flat Thermal Flux Meters (TFMs) were attached to the interior wall surfaces to measure heat fluxes through the walls (Figure 6). The measuring range and accuracy of the TFMs was $0-3.1 \times 10^5\text{ W/m}^2$ and 1% in departure of reading. Relative humidity (RH) was measured with relative humidity transducers. A tripod weather station was installed, which had a wind speed sensor, a pyranometer, and temperature and relative humidity probes. Year round outdoor weather conditions were monitored and measured.



Figure 5. Exterior wall thermocouples

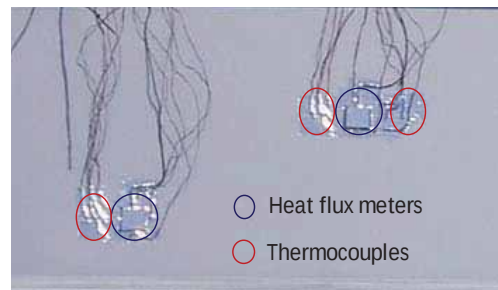


Figure 6. Thermocouples and heat flux sensors

3. Experiments

3.1. Calibration Experiments

It was necessary to perform calibration tests before any retrofit. For this, the thermal performances of the two houses were compared and recorded as baseline. Indoor air temperatures, wall temperatures, and heat fluxes were measured and compared to verify their similarity in thermal performance on June 23. This is shown in Figures 7 through 9. During the calibration period, the control house (House A) was kept at an average indoor air temperature of $24.17\text{ }^{\circ}\text{C}$, while the soon-to-be-retrofit house (House B) was kept at an average temperature of $24.22\text{ }^{\circ}\text{C}$. Figure 8 shows the similarity in temperature of the outside surface temperatures of the south-facing walls. Figure 9 shows the heat flux through the south-facing walls. The average difference in heat flux in the walls of both houses was in the range of 3%.

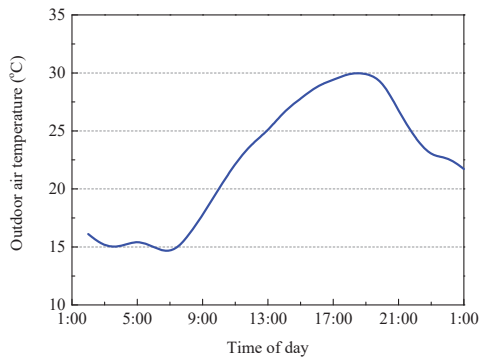


Figure 7. Outdoor air temperature during calibration period

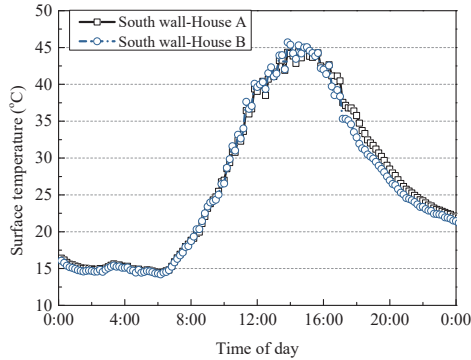


Figure 8. Outside surface temperatures on the south-facing walls during the calibration period

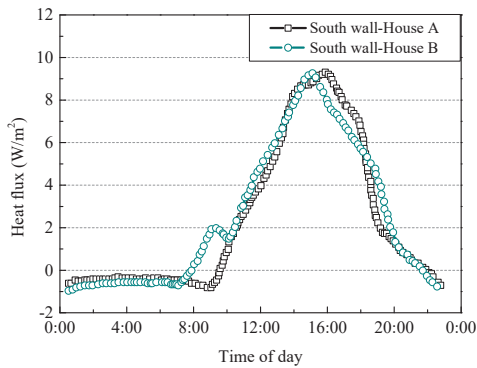


Figure 9. Wall heat flux through the south-facing walls during the calibration period

3.2. Results and discussion

The average reductions in peak heat fluxes as a result of using PCMs in frame walls in the north, south, east, and west walls were 33.7%, 25.6%, 24.3%, and 24.6%, respectively. The difference in peak heat fluxes of the aggregate between the control walls and the walls with PCMs at 10% concentration was approximately 27%. Figures 10 through 13 show the heat flux across frame walls facing various directions. It was found that the time shift was about one hour.

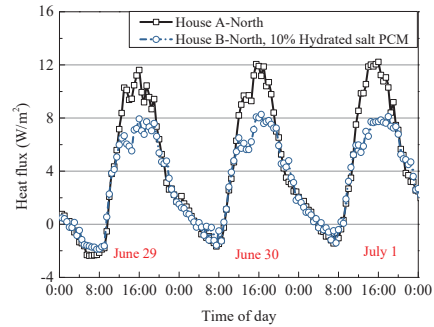


Figure 10. Heat flux through north-facing exterior frame walls at 10% PCM concentration

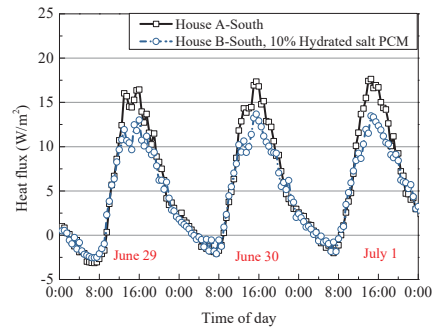


Figure 11. Heat flux through south-facing exterior frame walls at 10% PCM concentration

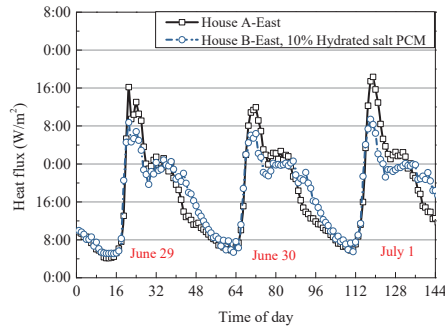


Figure 12. Heat flux through east-facing exterior frame walls at 10% PCM concentration

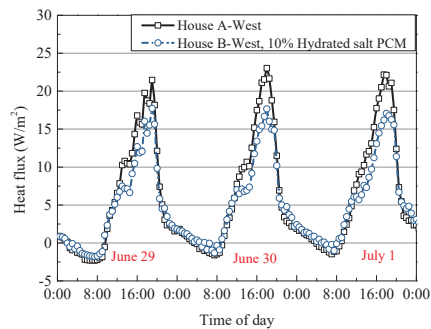


Figure 13. Heat flux through west-facing exterior frame walls at 10% PCM concentration

Figure 14 depicts how the walls outfitted with PCMs were able to keep a more constant inside wall surface

temperature and a narrower temperature fluctuation than the standard wall. Each segment shows indoor surface temperatures for a standard wall and for a wall outfitted with PCMs. For example, for the north walls the indoor surface temperature of the control house was on average 23.6 °C; while the surface temperature of the wall outfitted with PCMs was 22.5 °C. The temperature fluctuation in the standard wall was 2.2°C; while it was 1.1 °C for the wall outfitted with PCMs. It was noteworthy that the temperature variation of retrofit house (House B) was difference for walls with various orientations. On the north walls, the surface temperature in retrofit house had the lowest fluctuations and the temperature in control house was the lowest. In this case, it was guessed that the PCM was maintained partially melting or solidification process. Therefore, the PCM temperature was maintained at its phase change temperature. On the south and west walls, the temperature variation in retrofit and control houses followed the same trend. However, the variation was in a reverse trend for east walls. The surface temperature of south and west walls increased faster than it of east walls. That is, the heat transfer rate through south and west walls was larger, in which way the phase change process finished faster, resulted in a smaller time delay in peak temperatures and heat fluxes.

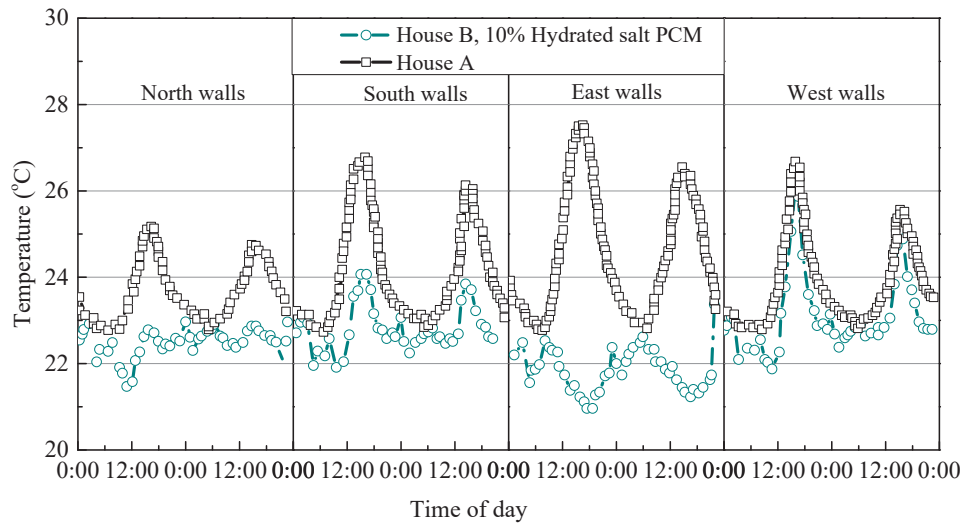


Figure 14. North, south, east, and west walls inside surface temperatures during calibration and retrofit tests at 10 % PCM concentration

Table 1 summarizes the findings related to the reductions in inside wall surface temperatures and in the daily temperature fluctuations. As stated above, it was observed that the walls with PCMs were able to not only lower the inside wall surface temperature of the walls, but also their daily temperature fluctuations.

The average reduction of inside wall surface temperature and daily temperature fluctuations were 1.5 °C and 1.4 °C, respectively. These results could translate to human comfort and to an increase in the life of comfort equipment with less on/off modes and operation time.

Table 1. Reductions in inside wall surface temperatures and reductions in temperature fluctuations produced by using PCMs at 10 % concentration

Wall Orientation	Average Surface Temperature (°C)		Difference (°C)	Average Temperature Fluctuation (°C)		Difference (°C)
	Control	Retrofit		Control	Retrofit	
North	23.6	22.5	1.1	2.2	1.1	1.1
South	24.1	22.8	1.3	3.7	1.9	1.8
East	24.4	21.8	2.6	4.2	1.4	2.8
West	23.9	22.9	1.0	3.4	3.4	0.0
Average	24.0	22.6	1.5	3.4	2.0	1.4

The same analyses were performed for a PCM at 20% concentration. The difference in peak heat fluxes and indoor surface temperatures between the control walls and the walls outfitted with PCMs were nearly the same as the values for the 10% PCM concentration. This means that doubling the amount of PCM did not produce significant improvement. Figures 15 through 18 show the heat fluxes through the north, south, east and west walls. The average reduction in peak heat transfer rates when using PCMs in the north, south, east and west walls were 27.1%, 29.2%, 25.7%, and 27.2%, respectively. From these results and aside from the north-facing wall, it was seen that doubling the quantity of PCM improved the performance by 3.6%, 1.4 %, and 2.6 % for the south, east, and west walls, respectively.

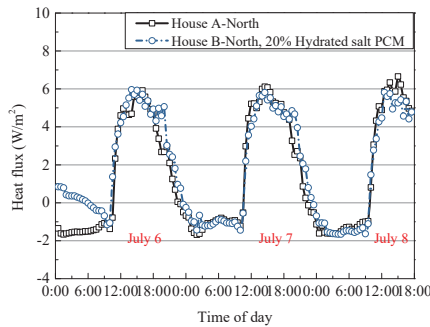


Figure 15. Heat flux through north-facing exterior frame walls at 20% PCM concentration

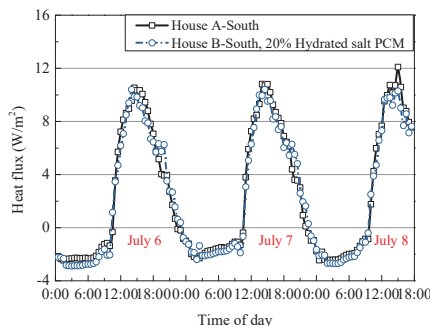


Figure 16. Heat flux through south-facing exterior frame walls at 20% PCM concentration

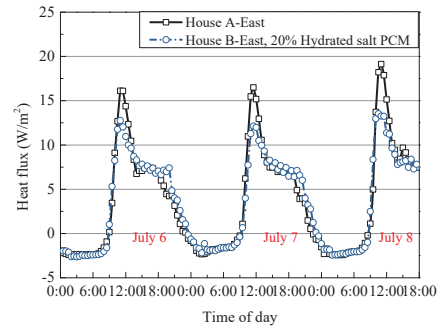


Figure 17. Heat flux through east-facing exterior frame walls at 20% PCM concentration

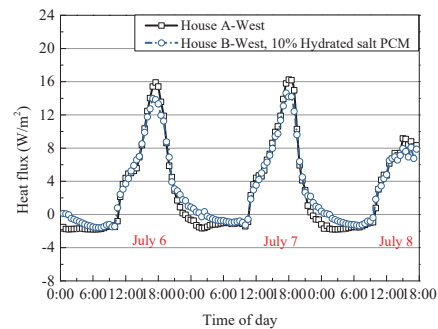


Figure 18. Heat flux through west-facing exterior frame walls at 20% PCM concentration

Table 2 summarizes the indoor surface temperatures in the control and the PCM-outfitted walls for a PCM concentration of 20%. The average indoor surface temperature of the four control walls was 23.9 °C while the indoor surface temperatures in the walls outfitted with PCMs was 22.4 °C. The average temperature fluctuation in the control walls was 3.2 °C while it was 1.7 °C in the walls outfitted with PCMs. The surface temperature of the walls outfitted with PCMs was also more constant than those for the control walls. This is shown in Figure 19.

Table 2. Reductions in inside wall surface temperatures and reductions in temperature fluctuations produced by using PCMs at a 20 % PCM concentration

Wall Orientation	Average Surface Temperature (°C)		Difference (°C)	Average Temperature Fluctuation (°C)		Difference (°C)
	Control	Retrofit		Control	Retrofit	
North	23.6	22.3	1.3	2.2	0.8	1.3
South	24.2	22.7	1.5	4.2	2.1	2.1
East	24.1	21.7	2.3	3.3	1.1	2.2
West	23.8	22.9	0.9	3.0	2.9	0.1
Average	23.9	22.4	1.5	3.2	1.7	1.4

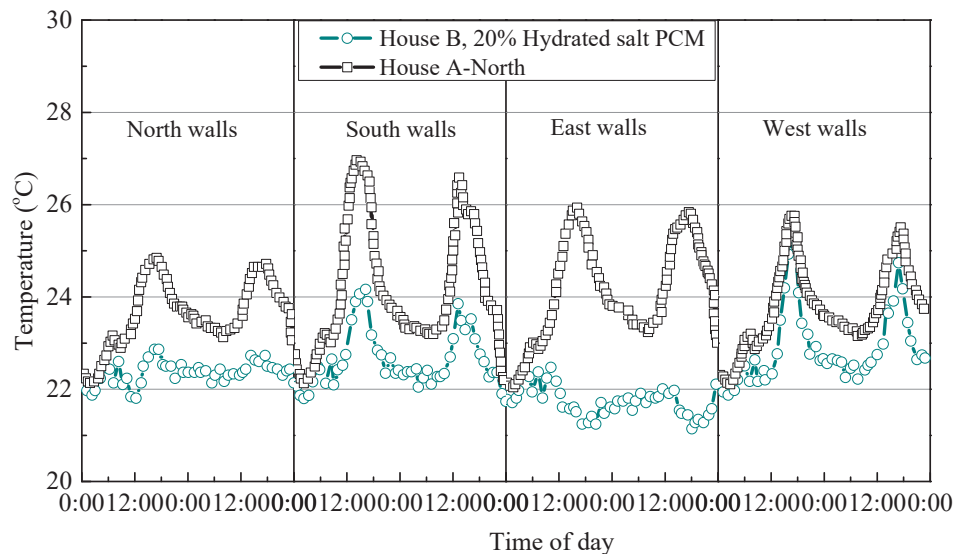


Figure 19. North, south, east, and west walls inside surface temperatures in calibration and retrofit tests at 20 % PCM concentration

reduction. Also, PCMs produced more stable wall temperatures, especially for north and east walls.

4. Conclusions

Heat transfer rates through frame walls with PCM encapsulated in copper pipes were investigated in well-controlled test houses under full weather conditions. It was found that PCMs produce reductions in heat flux, both in total heat flux and peak heat flux. Doubling the amount of PCM did not produce significant improvement on heat flux

Acknowledgements

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Impacts of large penetrations of distributed solar PV on Alberta's decarbonization plans

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Abstract:

Alberta's Climate Leadership Plan (CLP) sets a target for 30% of electricity to be generated by renewables. With approximately 1 million single detached homes in Alberta, there is the possibility that residential rooftop solar could contribute to this target. The decreasing capital costs of solar PV and their modular nature makes them a prime candidate to meet this demand. While the buildout of solar PV may aid in meeting Alberta's climate targets, the impact on the greater electricity and distribution system is less well understood. Through a scenario-based analysis, a dispatch optimization model is used to simulate detailed electricity generation for the year 2030. Specified PV penetration scenarios are based on four (4) major population centers of Alberta: Calgary, Edmonton, Lethbridge, and Medicine Hat. Four (4) scenarios to simulate adding a 5 kW solar PV system to various shares of the single detached housing stock. The ability of residential solar PV to contribute to the CLP's 30% target is analyzed as well as associated generation portfolio emissions. Results indicate that residential solar PV may not be beneficial in addressing the CLP renewable electricity target in large penetrations.

Keywords:

Distributed generation, Renewable integration, Power system modelling, Rooftop solar, Decarbonization

1. Introduction

In response to the growing concern over climate change, Canada has developed the Pan-Canadian Framework on Clean Growth and Climate Change. This plan includes carbon pricing, emissions reductions across all sectors of the economy, and the innovation and growth of the clean technology economy.

In 2015, the province of Alberta announced their Climate Leadership Plan. The plan includes a carbon levy, the phase out of coal-fired generation by 2030, capping oil sands emissions, reducing emissions, and the development of a generation portfolio that will provide 30% of Alberta's electricity via renewables by 2030. Beyond 30% capacity levels, integration becomes increasingly difficult and expensive [1].

Alberta's 2017 Long Term Outlook calls for 6445 MW of wind capacity and 700 MW of solar capacity by 2032 [2]. While currently, most of the 30% VRE energy target is set to be met by wind generation, this study aims to examine the implications of solar PV playing a larger role.

2. Methodology

This study utilizes PLEXOS® Integrated Energy Model to simulate hourly power generation over the course of the year 2030 [3]. Wind data for various locations in Alberta was obtained from the Alberta Electric System Operator (AESO). Alberta does not have commercially connected solar data from which to draw historic yearly data. Therefore, simulated solar PV generation from

various locations in Alberta is generated with PVWatts developed by NREL [4]. All generated data is for fixed roof mounted panels.

To simulate spatial resolution, wind data from 4 regions were used. The regions were split into North, South West, South Central, and South East. Solar PV data from PVWatts was generated for Calgary, Edmonton, Lethbridge, and Medicine Hat. Wind capacities are allocated regionally according to the AESO 2017 LTO.

3. Scenario Definition

Scenarios are defined by the percentage penetration of residential solar PV using Statistics Canada's 2016 housing census data [5]. Varying levels of PV are installed to meet Alberta's 30% renewable energy target. Installed capacity of wind and solar for each scenario are detailed in Table 1.

Table 1: Capacity of wind and solar modeled in 2030

Scenario	Wind capacity (MW)	Solar capacity (MW)
Base	6445	700
Scenario 1	6445	3212
Scenario 2	6445	4732
Scenario 3	700	6445

The base scenario are the capacity targets for 2032 from the AESO 2017 Long Term Outlook. Scenario 1 results are representative of a 5 kW residential solar PV system being installed on the roof of every single-detached home in the metropolitan areas of Calgary,

Edmonton, Lethbridge, and Medicine Hat. Scenario 2 is representative of a 5 kW residential solar PV system being installed on every single-detached home in Alberta. Scenario 3 is set to examine the impacts on emissions if the 2017 LTO targets were to be met with much of the capacity in residential solar PV.

4. Results and discussions

Annual 2030 energy generation is simulated and compared to total yearly generation to determine if the 30% renewable electricity generation (energy) target is met. The portion of total energy supplied by modeled residential solar PV in each scenario is calculated. Results are detailed in Table 2.

Table 2: Annual percentage of total generation of renewable energy generated and solar energy generated

Scenario	Renewable energy generated	Solar energy generated
Base	31%	1%
Scenario 1	35%	5%
Scenario 2	38%	8%
Scenario 3	19%	11%

It is seen from Table 2 that renewables, including residential solar PV, wind, hydro, and biomass, can meet Alberta's 30% renewable electricity target by 2030 with these portfolios. Hydro and biomass are small in installed capacity compared to wind and solar and therefore are not explored in the modelling process. When examining Scenario 3 where residential solar PV can play a large role in comparison to wind, the RE 30% target is not met. This is due to the lower capacity factor of residential solar PV. This is seen again when examining the percentage of total generation from solar. In every scenario, solar can generate only between 1-11% of total generation.

A residual load duration curve is calculated for each scenario, shown in Figure 1 compared to projected 2030 load. The residual load duration curves account for wind and solar PV only, not the small portion of other renewables in the Alberta system. As evidenced by the results, no scenario studied is able to reduce peak load hours by providing reliable capacity. The flatter the LDC, the easier the scenario is for the remainder of the system to handle. A flatter curve means less ramping events necessary and the ability for dispatchable generation to run at a higher capacity factor through the year.

Scenario 3 has the flattest curve due to the lower energy output of residential solar PV as compared to the higher wind penetration scenarios. The Base scenario as well as Scenarios 1 and 2 are all grouped tightly together due to the high penetrations of wind with larger capacity factors causing more variability in the system. While flatter curves are easier to deal with,

that does not mean they are most beneficial in terms of decarbonization.

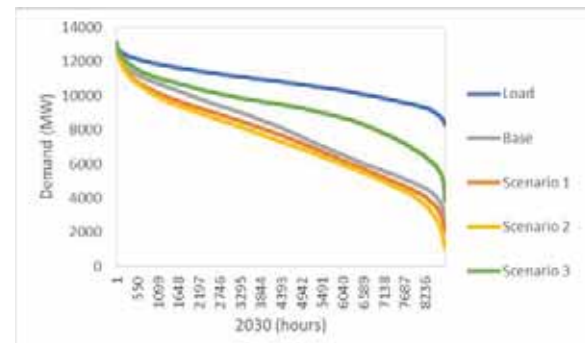


Figure 1: Load duration curve for all scenarios in the year 2030

When examining generation portfolio options, it is important to understand CO₂ emission levels. Emissions from the operation of natural gas fired cogeneration plants, combined cycle plants, and simple cycle plants are simulated throughout the year based upon their optimized generation patterns. Yearly emissions are then summed and compared in Table 3.

Table 3: Simulated 2030 yearly emissions for 4 studied scenarios

Scenario	2030 Emissions (Mt CO ₂)	Emissions abatement from Base
Base	12.4	
Scenario 1	11.0	11%
Scenario 2	10.2	18%
Scenario 3	16.2	- 31%

In analyzing results from Table 3, it is seen that Scenario 3 increases emissions from the current Base target case by 31%. While this option was the most manageable operationally from a grid perspective, the decreased energy output from the lower capacity factor residential PV systems does not compete with commercial wind farms.

The ability to integrate these scenario generation portfolios can be analyzed via ramping events in cogeneration and combined cycle capacity. Single cycle capacity is also installed but used infrequently and therefore not examined here. Histograms are created to examine the frequency of ramping events for cogeneration capacity and combined cycle capacity and are detailed in Figures 2 and 3, respectively.

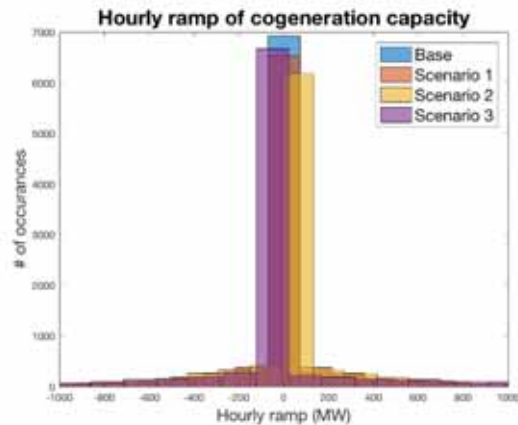


Figure 2: Histogram of ramping events in cogeneration capacity for 4 scenarios

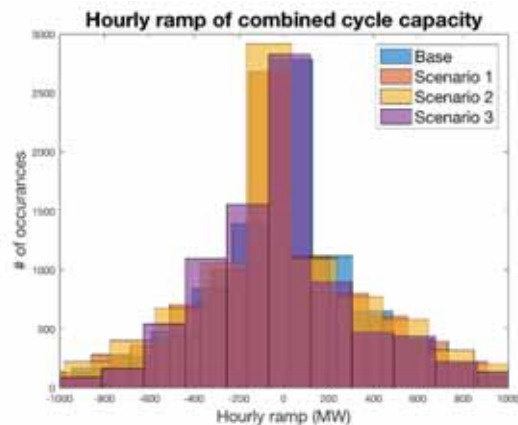


Figure 3: Histogram of ramping events in combined cycle gas turbine capacity for 4 scenarios

Figure 2 showing the occurrence of ramping events in cogeneration capacity shows little change between scenarios. Much of cogeneration capacity installed is must-run generation, meaning there is little room for ramping events to occur. The large bar shows that the remaining available cogeneration capacity is used for small ramping events, which are lowest in Scenario 2. These are used often to manage mostly small changes in variable renewable output.

Figure 3 showing the occurrence of ramping events in combined cycle capacity. Combined cycle gas turbines provide fast ramping and load following abilities. It can be seen here that the combined cycle gas turbines operate to deal with larger changes in variable renewable energy generation as well as load changes. The 4 scenarios imposed on the AESO 2017 LTO 2032 portfolio appear to be manageable by the associated natural gas fleet of generators.

5. Conclusions and outlook

In the future, many jurisdictions will likely have high penetrations of VRE. Residential solar PV utilizes rooftop area and allows for generation to be spatially

diverse, thus smoothing some variability associated with the technology. This research analyzes various scenarios of residential solar PV and wind capacity generation over the year 2030 to examine the value residential solar provides to Alberta's Climate Leadership Plan 30% renewable electricity target.

Results indicate that the low capacity factors of residential solar PV do not allow it to take place of similar capacities of commercial wind projects. All scenarios are technically feasible after examination of ramping events imposed on the natural gas generation fleet. Of the scenarios examined, Scenario 2 provides the greatest benefit to displacing fossil fuel generating capacity while reducing emissions greater than any other scenario studied.

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Entrepreneurship and African Urban Infrastructure: Seeking the Intersection

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Abstract:

The projected explosive future growth of African cities will strain efforts to develop supporting infrastructure. Simultaneously Africa's potential rise as an entrepreneurial powerhouse will be increasingly evident on a global scale. Can these two worlds meet? – can the benefits of the powerful model of technology innovation, entrepreneurship, and risk capital play a role in solving Africa's looming urban infrastructure gap? Cell phone networks in the telecom sector are widely acknowledged as an entrepreneurial leapfrogging of traditional networks. Trends in the nascent area of ride sharing – the rise of Uber and similar services - may provide additional clues in the transportation segment. In Africa and in other high growth developing economies, such as those in South and Southeast Asia, ride sharing services may indicate that entrepreneurial approaches can displace some (but not all) of what has been traditionally viewed as an infrastructure provision burden for governments and multilateral bodies. Are there other key segments of urban infrastructure where this same trend may surface? We look at the cases of urban energy generation, of housing and green buildings, and "smart cities" technologies through the lens of entrepreneurial activity and sustainability. Many questions and implications unfold, some of which we raise and briefly address.

Keywords:

Entrepreneurship; Sustainable Cities; Infrastructure, Africa

1. Introduction

In recent years at the University of Toronto (UofT) we have traveled to a range of African cities as part of a project entitled "Engineering Education for Sustainable Cities in Africa" (EESC-A). Among many other avenues this work has led us to contemplating the role of entrepreneurship in building the future required urban Infrastructure in Africa.

These are two words that are not heard together very often in the west – infrastructure and entrepreneurship. I will argue perhaps there is a leapfrogging opportunity in that intersection that is unique to Africa - it lies before those who will build future African cities, and those educating them today.

2. Sustainable Mega-Cities in Africa

A colleague on our project, Prof. Daniel Hoornweg and his colleague Kevin Pope reconciled estimates of future populations of world cities [1]. They specifically looked at the case of 2050 and 2100. Their analysis shows a striking result – based on consensus estimates by 2100, 13 of the largest 20 cities in the world are in Sub-Saharan Africa (SSA).

Furthermore the largest of those cities is enormous. So, cities like Lagos and Dar es Salaam, which currently face substantial infrastructure problems, will in the future support over 70 million inhabitants. Hoornweg and Pope's work suggest multiple questions including: (1) how does the infrastructure get built? (2) can that infrastructure be sustainable – in the economic and the environmental sense of the word? (3) how can

Africa produce the very large number of skilled infrastructure engineers required?

Table 1: African cities are among the largest in world in 2100. Source: Hoornweg & Pope [1]

World ranking 2100	City name	Population (millions)
1	Lagos, Nigeria	88
2	Kinshasa, DRC	83
3	Dar es Salaam, Tanzania	74
6	Khartoum, Sudan	57
7	Niamey, Niger	56
12	Nairobi, Kenya	47
13	Lilongwe, Malawi	41
14	Blantyre City, Malawi	41
15	Cairo, Egypt	41
16	Kampala, Uganda	40
18	Lusaka, Zambia	38
19	Mogadishu, Somalia	36
20	Addis Ababa, Ethiopia	36

3. An Entrepreneurial Approach

Globally we are very familiar with new industries created by a unique combination – innovative technology, an entrepreneurial company, and risk capital sources to finance the new company. That

mixture has built new industries in North America in particular and globally – semiconductors, software, biotechnology – and rejuvenated selected other industries, such as steel and commercial aviation. And in recent decades there have been movements to broaden the formula to include products and services with strong environmental benefits (“cleantech”) and to achieving broader social benefits (“impact investing”), in some cases investing in enterprises focused on delivering good and services to the poor in developing regions [2].

Africa is full of examples of entrepreneurship - some in formal economy, much in the informal sector. In the former case there is a growing sample of entrepreneurial companies in Africa. But we generally think of those in knowledge industries like software and e-commerce. But isn't urban infrastructure certainly a knowledge industry?

So can these two concepts be brought together to benefit African cities? The projected explosive future growth of African cities will strain efforts to develop supporting infrastructure. Simultaneously Africa's potential rise as an entrepreneurial powerhouse will be increasingly evident on a global scale. Can these two worlds meet? – can the benefits of the powerful model of technology innovation, entrepreneurship, and risk capital play a role in solving Africa's looming urban infrastructure gap?

4. Segments and Cases

This paper is submitted to a 2018 conference about various forms of infrastructure, set in North America. If we had a conference in 1987 on telecom industry in Africa, we can think about what would have been earnestly discussed for multiple days. The topics would have been quite off the mark in terms of how the telecom industry on Africa evolved over the next 30 years.

So we know about the impact of cell phone on telecom – that is like driving looking in the rear view mirror. Cell phone networks in the telecom sector are widely acknowledged as an entrepreneurial leapfrogging of traditional technologies. But can we learn from that case about urban infrastructure? – the advantages and resilience of smaller scale, decentralized solutions.

One area where decentralized, entrepreneurial approaches are evident in Africa is renewable energy. The many examples include home solar systems, village level mini grids, and even wheeling – a mini grid feeding the main grid. So this is in some ways a race between the big guy – the grid – and the little guy – decentralized systems. As we learned from cell phones, sometimes the little guy will win.

We see similar evolution beginning in housing. There are huge housing needs and shortages in African cities, and elsewhere in the world. Yet the construction

industry is a rare one where productivity growth is negative [3]. There will be a strong movement to modular housing solutions, manufactured in factories – the future “house in a box” [4]. There are experiments, notably in China, with 3D printing of components of high rise buildings. And there will be significant advances in the adoption of essential seismic engineering strategies in low cost housing solutions, a topic of research at UofT.

5. Transportation Sector and Entrepreneurship

A particular striking example of entrepreneurial approaches is in some aspects of urban transportation – a sector where smaller scale solution may be valuable. One African example is Mobius Motors, an audacious venture building light vehicles for the African context. The existence of a low cost vehicle will unlock the potential for providing many types of service delivered by individual entrepreneurs. The vehicle is sufficiently versatile it could provide various services over the course of a day –a delivery vehicle for transporting light goods from farm to market, then a school bus, then an ambulance for non-emergency uses.

But what if those types of services can be organized more formally, provided some start up capital, and enabled by technology? We have a striking example already – analogous to cellphones in 1984 – in the form of Uber and other vehicle sharing services. I was inspired by a recent talk by the General Manager of Uber Africa, Alon Lits, at a conference [5]. It seemed clear Mr. Lits was thinking of Uber as a partial substitute for urban transit systems in developing economies. He posited the following. If one was creating a bus line to pick up passengers within say 15 minutes of being called and take them where they are going, how much would that cost in a conventional city bus system? Uber provides the potential to provide that service with vehicles that already exist and are paid for privately. A recent article looked at Uber in India [6]. It asked why do we need one car per family? In Africa and elsewhere in the developing world ride sharing could leapfrog and change what personal transportation looks like.

A further example is Go-Jek and its competitors in Indonesia – a ride-sharing service using scooters. We saw a less formal version in Dar es Salaam – but without the technology-enabled aspect of Go-Jek. Via is a popular service presently in New York City - an online version of the African share-taxi (or daladala or tro-tro or combi or etc). So Via is reverse innovation from Africa to the West – we can expect much more of that.

In Africa and in other high growth developing economies such as those in South and Southeast Asia, ride sharing services may indicate that entrepreneurial approaches can displace some (but not all) of what has been traditionally viewed as an infrastructure provision

burden for governments and multilateral bodies. But there is a need for formal entrepreneurial structures, risk capital, and technology adapted to a specific setting, including the habits and preferences of local end users. Transportation services will be driven by information technology – quite literally with the adoption of self-driving vehicles. When Uber selected a new CEO in 2017 it passed over as a finalist candidate Jeff Immelt, previously CEO of General Electric, in favor of selecting between two candidates with stronger software experience.

These examples lead to the broader case of smart cities – and the leapfrogging opportunity they present. Africa can utilize the concept of “digital twins,” i.e. modeling systems that simulate a specific real-world infrastructure system and allow optimization, preventative maintenance, and problem solving. Such solutions are already in use in various energy technologies, such as turbines. There is an opportunity to leapfrog in other infrastructure areas. The ubiquitous and growing delays on New York City subway lines stems from the use of decades-old switching technologies. The legacy systems are so inaccurate and unreliable that trains must be spaced at great distances apart to avoid accidents due to systems malfunctions [7]. Other modeling tools relevant to urban settings include GIS, and crowdsourcing approaches like Open Street Map. Ushahidi in Kenya is already a leader in crowdsourcing approaches to city trouble spots, such as post-election riots or unsafe areas.

Alphabet/Google has set up Sidewalk Labs, headquartered in New York City, to develop smart cities technologies. Although its first major test site is a waterfront area in downtown Toronto, presumably Africa could be a great setting for urban redevelopment approaches and technologies.

6. Conclusions, Implications and Outlook

So many of the above examples of future innovations in cities engineering can be knit together by entrepreneurial vision and smaller scale approaches. Many questions unfold when we examine African urban infrastructure through the lens of entrepreneurial activity and sustainability. One question concerns how to build such organizations. How do you build more entrepreneurial SMEs in knowledge sectors (broadly defined), and how do you embed entrepreneurial thinking into large organizations like MNCs, multilateral agencies like the World Bank, and even governmental entities.

There is also a question of enabling the special role of higher education in engineering and other professions. We have seen innovation both at traditional universities and at emerging alternative models. Innovations include online and distance learning approaches, including those that might be developed collaboratively with western educational institutions. New skills can be

integrated into the curriculum – at the University of Dar es Salaam entrepreneurship is mandatory for undergrads. Other institutions such as the University of Zambia and Copperbelt University are integrating sustainability across programs. And there are new and innovative institutions – examples like African Leadership University, Kepler and Ashesi, and in the private sector Andela, a company that provides high level, on-the-job training in software coding.

The above also suggests the question of the most helpful and appropriate role for those of us in the west. Can we help Africans build the solutions they consider best for their future, and what are the various mechanisms to do that at scale in a cost-effective way?

Africa and Africans have the opportunity to build cities that are better than the west. Are there any great western cities, when you look at GHG footprint and the crushing cost of infrastructure maintenance? Is there a more sustainable model for African cities versus the traditional model of “great” western cities – defining sustainable from both an economic and from an environmental perspective?

So we can ask what will become will be the great African city of the future – hopefully there will be many. The whole world depends on that – it will depend on what Africans decide. And perhaps more it will depend on the decisions of the future engineers that Africa is educating now and in the next few decades. How can Africa educate engineers who not only build infrastructure but who are global, sustainable, urban engineering leaders and entrepreneurs?

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Evaluation of the long-term performance of vacuum insulation panels installed in real building environments

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Abstract:

Vacuum insulation panels (VIPs) are used to enhance the energy efficiency of devices including refrigerators, vending machines, and cooler boxes. The VIP core is composed of glass wool or fumed silica and covered by a laminated film. Upon evacuating the air from the VIP, the gas thermal conductivity can be reduced to near zero, resulting in good thermal performance. VIPs have recently been considered for application in houses and other buildings; however, an accurate prediction of the long-term thermal performance of VIPs in buildings is difficult. This study attempts to clarify the long-term performance of a VIP exposed to a realistic building environment. Based on the correlation between internal pressure and thermal conductivity, we developed a micro-pressure sensor that can be inserted inside the VIP to accurately measure the pressure and evaluate the thermal conductivity at the construction site. This sensor makes it possible to directly measure the performance of a VIP within a wall.

Keywords:

Vacuum insulation panels, Measurement technique, Microsensor, Prediction of long-term performance

1. Introduction

Vacuum insulation panels (VIPs) are high-performance insulating materials constructed by covering a core and adsorbent with an envelope and evacuating the air from the inside. VIPs are widely used in refrigerators and vending machines, wherein they improve the energy efficiency. In recent years, insulating materials, such as VIPs, have attracted attention for application in houses and other buildings to improve heat insulation and energy efficiency. However, to apply VIPs as heat-insulation materials in houses, it is necessary to predict the long-term performance of the VIP and verify the accuracy of the prediction using actual measurements. In past studies, it was impossible to directly measure the thermal performances of VIPs applied in houses. To solve this problem, we developed a micro-pressure sensor that can be inserted inside the VIP to measure its long-term performance after construction. Since the internal pressure is correlated with thermal conductivity, it is possible to measure the change in thermal conductivity by measuring the change internal pressure over time. In this study, we evaluated the effect of the external environment on the VIP by directly measuring the internal pressure of the VIP using the micro-pressure sensor. The remainder of this paper discusses the micro-pressure sensor, the calibration of the sensor, and the long-term performance of a VIP installed in the OA floor of a building.

2. Aging model [1] [3]

The parallel model is widely used to predict thermal conductivity. Heat transfer in the core material can be expressed as the conduction through solid and through gas in case of its presence and radiation:

$$\lambda_{cop} = \lambda_s + \lambda_g + \lambda_r, \quad (1)$$

where λ_{cop} is the thermal conductivity of the center of the panel, λ_s is the thermal conductivity of the solid skeleton, λ_r is the radiative thermal conductivity, and λ_g is the thermal conductivity of the gas within the pores.

The units for all variables are provided in the Symbols section at the end of the paper. The thermal

conductivities of the solid and gaseous components of the VIP are affected by the internal pressure and adsorption of water vapor on the core material.

2.1 Thermal conductivity of the VIP with desiccant

The thermal conductivity of the VIP containing desiccant can be expressed as

$$\lambda_{cop} = \lambda_{sr,int} + \lambda_g(P_{a,T}) = \lambda_{sr,int} + \lambda_{ga}. \quad (2)$$

2.2 Permeability of dry air

Based on the mass-balance equation for air permeation into the VIP and the state equation of an ideal gas ($P_i V_{eff} = m_i / M_i RT$), the change in internal pressure resulting from the permeation of dry air can be expressed by

$$\frac{dm_a}{dt} = \frac{M_a \cdot V_{eff}}{R \cdot T} \cdot \frac{dP_a}{dt} = K_{a,total} \cdot (P_{a,atm} - P_a) \quad (3)$$

$$P_a = P_{a,atm} - (P_{a,atm} - P_{a(0)}) \exp\left(-\frac{K_{a,total} RT}{M_a V_{eff}} t\right) \quad (4)$$

2.3 Permeability of water vapor in a constant environment

When the desiccant is functioning, the changes in water vapor pressure are negligible. Under a constant environment, the permeability of water vapor M can be expressed as

$$M = \int_0^t g dt = \int_0^t K_{v,total} (P_{v,atm} - 0) dt = K_{v,total} \cdot P_{v,atm} \cdot t, \quad (5)$$

$$K_{v,total} = \frac{M}{P_{v,atm} \cdot t}. \quad (6)$$

By selecting the amount of desiccant based on the permeability of water vapor and the service life of the VIP, it is possible to suppress the internal water vapor pressure in the VIP using a glass-fiber core material.

2.4 Relation between gas permeability and dimensions

The total transmittance $K_{i,total}$ ($i = a, v$) can be expressed in terms of the transmittance per unit area $K_{i,A}$, the transmittance per unit length $K_{i,L}$, and the transmittance from the defect per unit area as follows:

$$K_{i,total} = K_{i,A} \cdot A + K_{i,L} \cdot L + K_{i,P} \cdot A \quad (7)$$

2.5 Thermal conductivity due to difference dimension (Al foil) [3]

For an aluminum foil VIP, the transmittance from the surface can be assumed to be close to 0. Assuming there are no defects, the transmittance of the aluminum foil VIP can be expressed as

$$K_{a,total} = K_{a,L} \cdot L \quad (8)$$

Based on the measured values of a certain dimension, with perimeter length L_{ref} , the change in internal pressure is expressed as

$$\frac{dP_{Aref,Lref}}{dt} \cong (P_{a,atm} - P_a(0)) \frac{K_{a,L} \cdot L_{ref} RT}{M_a V_{eff}(ref)} \quad (9)$$

Based on the internal pressure increasing at the reference perimeter length L_{ref} , we calculate the amount of increasing internal pressure with an arbitrary length L :

$$\begin{aligned} \frac{dP_{A,L}}{dt} &\cong (P_{a,atm} - P_a(0)) \frac{K_{a,L} \cdot L_{ref} RT}{M_a V_{eff}(ref)} \cdot \frac{V_{eff}(ref)}{V_{eff}} \cdot \frac{L}{L_{ref}} \\ &= \frac{dP_{Aref,Lref}}{dt} \cdot \frac{V_{eff}(ref)}{V_{eff}} \cdot \frac{L}{L_{ref}} \end{aligned} \quad (10)$$

$$P'_{t,A,L} = P'_{t,Aref,Lref} \cdot \frac{V_{eff}(ref)}{V_{eff}} \cdot \frac{L}{L_{ref}} \quad (11)$$

2.6 Thermal conductivity owing to difference in dimensions (metallized film) [3]

Unlike the aluminum foil VIP, considering the transmittance from the surface, the transmittance of the metallized VIP is expressed as

$$K_{a,total} = K_{a,A} \cdot A + K_{a,L} \cdot L \quad (12)$$

Based on the measured value at a certain dimension, for a surface area A_{ref} and perimeter length L_{ref} , the change in internal pressure is expressed as

$$\frac{dP_{Aref,Lref}}{dt} \cong (P_{a,atm} - P_a(0)) \frac{K_{a,total}(ref) RT}{M_a V_{eff}(ref)}, \quad (13)$$

$$\begin{aligned} \frac{dP_{A,L}}{dt} &\cong (P_{a,atm} - P_a(0)) \frac{K_{a,total} \cdot L_{ref} RT}{M_a V_{eff}(ref)} \cdot \frac{V_{eff}(ref)}{V_{eff}} \cdot \frac{K_{a,total}}{K_{a,total}(Aref,Lref)} \\ &= \frac{dP_{Aref,Lref}}{dt} \cdot \frac{V_{eff}(ref)}{V_{eff}} \cdot \frac{K_{a,total}}{K_{a,total}(Aref,Lref)} \end{aligned} \quad (14)$$

$$P'_{t,A,L} = P'_{t,Aref,Lref} \cdot \frac{V_{eff}(ref)}{V_{eff}} \cdot \frac{K_{a,total}}{K_{a,total}(Aref,Lref)} \quad (15)$$

2.7 Relation of dry air pressure and thermal conductivity

Since the thermal conductivity of the VIPs relate to the internal pressure of VIPs, it can be expressed as follows using the Eqs. (3) and (7).

$$\lambda_{cop} = \lambda_{sr,ini} + \lambda_{ga} = \lambda_{sr,ini} + \frac{\lambda_{ga,0}}{1 + \frac{P_{1/2}}{P_a}} \quad (16)$$

$$\lambda_{cop} = \lambda_{sr,ini} + \frac{\lambda_{ga,0}}{1 + \frac{P_{1/2}}{P_{a0} + P'_{a,t} \cdot t}} \quad (17)$$

From the time rate of the internal pressure, the relation of time rate of thermal conductivity can be obtained.

2.8 Estimation of transmittance under different conditions (Arrhenius plot) [3]

Supposing that the temperature and pressure of the environmental conditions to be found are $(T_{ex}, P(T_{ex}))$, from Eq. (6), the gas permeability $K_{a,total}$ of dry air is as follows:

$$K_{a,total} = \frac{1}{(P_{a,atm} - p(0))} \cdot \frac{M_a V_{eff}}{RT_{ex}} \cdot \frac{dP(T_{ex})}{dt} \quad (18)$$

When calculating the time rate of internal pressure from the measurement result of the thermal conductivity, it is necessary to convert by the average temperature at the time of measuring the thermal conductivity and the pressure $(T_c, P(T_c))$.

$$P(T_{ex}) = \frac{P(T_c)}{T_c} T_{ex} \quad (19)$$

Substitute this equation into Eq. (18),

$$K_{a,total} = \frac{1}{(P_{a,atm} - p(0))} \cdot \frac{M_a V_{eff}}{RT_c} \cdot \frac{dP_a(T_c)}{dt} \quad (20)$$

When estimating the transmittance under different environmental conditions of the same size, approximate expressions for arbitrary temperature conditions are calculated from Arrhenius plot. In addition, by examining the dependence on temperature and humidity, the temperature and humidity dependency can be calculated. When the transmittance depending on temperature and humidity is $K_{a,total}(T,H)$, $K_{a,total}(T,p)$ (H: relative humidity[%], p: water vapor pressure [Pa]), the internal pressure increasing formula at the reference temperature condition $T_{ref}^\circ \text{C}$, $H_{ref}\%$ is as follows.

$$\frac{dP(T_{ref})}{dt} \cong (P_{a,atm} - P_a(0)) \frac{K_{a,total}(T_{ref}, H_{ref}) RT_{ref}}{M_a V_{eff}} \quad (21)$$

$$\begin{aligned} \left(\frac{dP(T_c)}{dt} \right)_{(T_{ref}, H_{ref})} &= \frac{T_c}{T_{ref}} \frac{dP(T_{ref})}{dt} \\ &\cong (P_{a,atm} - P_a(0)) \frac{K_{a,total}(T_{ref}, H_{ref}) RT_c}{M_a V_{eff}} \end{aligned} \quad (22)$$

$$\begin{aligned} \frac{dP(T)}{dt} &\cong (P_{a,atm} - P_a(0)) \frac{K_{a,total}(T,H) RT}{M_a V_{eff}} \\ &= \left(\frac{dP(T_c)}{dt} \right)_{(T_{ref}, H_{ref})} \cdot \frac{K_{a,total}(T,H)}{K_{a,total}(T_{ref}, H_{ref})} \cdot \frac{T}{T_c} \end{aligned} \quad (23)$$

$$P'_{t(T,H)} = \left(\frac{dP(T_c)}{dt} \right)_{(T,H)}, P'_{t(T_{ref}, H_{ref})} = \left(\frac{dP(T_c)}{dt} \right)_{(T_{ref}, H_{ref})}$$

$$P'_{t(T,H)} = P'_{t(T_{ref}, H_{ref})} \cdot \frac{K_{a,total}(T,H)}{K_{a,total}(T_{ref}, H_{ref})} \quad (24)$$

3. Micro-pressure sensor

To measure the internal pressure of a VIP over a long time period, we developed a micro-pressure sensor (Fig. 2). The micro-pressure sensor comprises (1) a vacuum sensor, (2) thermo-hygrometer, (3) small battery, (4) wireless transmission device, and (5) charging section. The sensor is designed to allow two types of power supply systems with different charging

methods (the electromagnetic dielectric method and Peltier element). The charging time is approximately 5–10 min, and one charge allows one week of measurements at the measurement intervals of 10 min. The sensor can receive data from the VIP within a distance of 5 m. The micro-pressure sensor was calibrated using a capacitance manometer (Fig. 1; CCMT-D made by ULVAC). The output of the micro-vacuum sensor is a dimensionless quantity. Because each micro-vacuum sensor will differ in performance, each sensor must be calibrated separately.

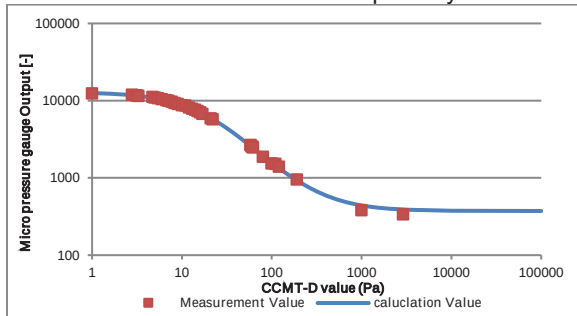


Fig. 1. Micro-pressure gauge proofreading data



Fig. 2. Image showing the micro-pressure sensor inside a VIP

4. Long-term VIP performance in the laboratory
In order to confirm the gas permeability (K_{air_total}) of the dependence of temperature and humidity, we carried out the aging test with thermostatic chamber. The Arrhenius plot was obtained based on Eq. (27). The details of the experimental VIPs are shown in Table 1. The Arrhenius plot does not consider the gas absorbed by the getter material.

Table 1. Details of the VIP and aging conditions

VIP Size	t10 x 495 x 495 C4'
Core	Glass fiber 1
Film	Hybrid Type
Desiccant	Calcium Oxide
Getter	Zeolite type
Protection	Covered by PVC 75μm film
Aging condition	1) 23°C, 50% RH 2) 35°C, 80% RH 3) 50°C 4) 50°C, 70% RH
	

*The four corners of the VIP contain 90-mm cutouts

4.1 Long-term VIP performance in a thermostatic chamber

The VIP was removed from the thermostatic chamber and cured at room temperature. The thermal conductivity was then measured using a heat flowmeter (HC074 600, EKO instruments), and the

results are shown in Fig. 3, Fig. 4, and Table 2. The Arrhenius plot is shown in Fig. 5. The Arrhenius plot confirmed the temperature dependence of the VIP air permeability under the tested aging conditions (23°C, 50% RH; and 50°C). The comparison of the aging conditions of 50°C and 50°C with 70% RH confirmed that the gas permeability increased by approximately 6%. Based on Fig. 4, no weight change in the VIP was observed during aging at 50°C, whereas the weight increased by 0.0133 g/day under 50°C with 70% RH. During aging at 35°C and 80% RH, the weight increased by 0.0036 g/day. However, since 35°C with 80% RH is in agreement with the Arrhenius plot, it is considered that the gas permeability generally agrees with that at 35°C. In contrast, at 50°C and 70% RH, K_{air_total} increased by 6% compared to the VIP aged at 50°C. The transmittance of dry air increased with RH. The metallized film is provided with a vapor deposited layer based on EVOH, probably because the barrier property of the EVOH layer decreased under high temperature and high humidity.

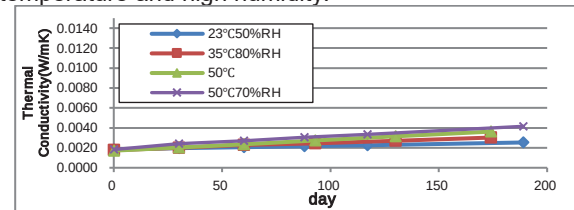


Fig. 3. Long-term performance of the VIP under different static conditions

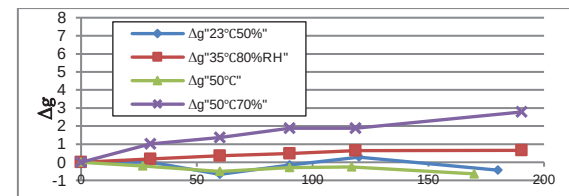


Fig. 4. Increase in weight of the VIP under different static conditions

Table 2. Overall air Permeability (K_{air_total}) of the VIP aged under different conditions

Temperature (T, °C)	Relative Humidity (RH; %)	1/T	K_{air_total} [$\times 10^{-12}$ g/day·Pa]
23	50	0.00337	14.3
35	80	0.00325	21.0
50	-	0.00309	35.8
50	70	0.00309	37.7

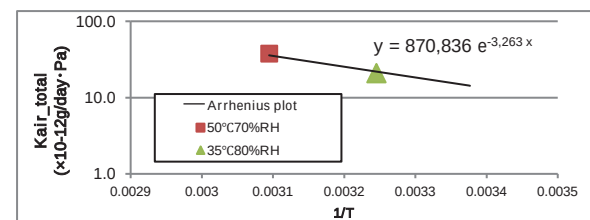


Fig. 5. Arrhenius plot of the VIP of hybrid type

4.2 Long-term performance of the VIP on site conditions

The VIPs were spread on the concrete slab under the OA floor of a new building (Fig. 6), and the thermal conductivity along with the environmental conditions over time (Fig. 9) was measured. Thermo-hygrometers were installed on the front and back of each VIPs to measure the temperature and humidity (Figs. 7 and 8).

The VIPs were removed from under the floor every three months, and their weights and thermal conductivities were measured before reinstallation. The details of the VIPs and the installation periods are shown in Tables 3 and 4, respectively. Half of the VIP installed in Room 2 (VIP01) was placed in the reverse of the front and back, and the effect of the orientation of the MF surface on the long-term VIP performance was evaluated. First of all, we obtained the total gas permeability (K_{air_total}) based on the values of internal pressure which is calculated from measurement value of thermal conductivity.

Table 3. Characteristics of VIPs used in the test of real-world conditions

VIP Size	① t10 × 495 × 495 C4*1 ② t10 × 372 × 385 ③ t10 × 372 × 385
Core	① Glass fiber 1 ② Glass fiber 2 ③ Glass fiber 1
Film	Hybrid Type
Desiccant	Calcium Oxide
Getter	Zeolite type
Protection	Covered by PVC 75-μm film
	

*The four corners of the VIPs have 90-mm cutouts

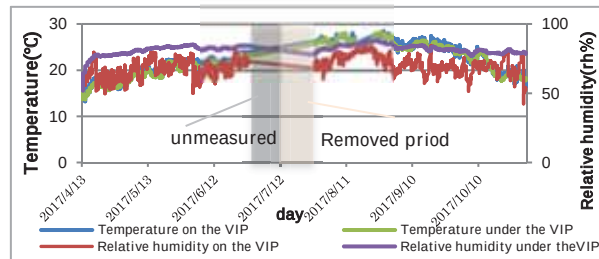


Fig.7. Temperature and relative humidity measured in room 1 on and under the VIP

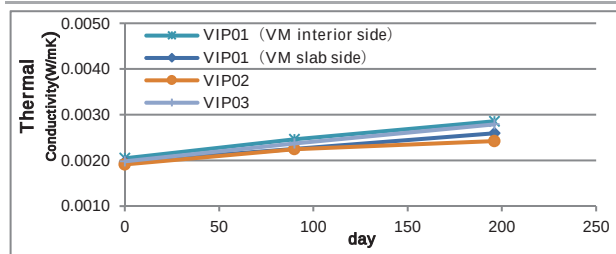


Fig.9. Long-term performance of the VIPs in different rooms and comparison of inside out

Secondly, table5 shows a comparison of the internal pressure obtained from the time rate of thermal conductivity " ΔP_m " and the time rate of temperature data " ΔP_{cal} ". ΔP_{cal} was obtained total gas transmittance on site conditions which is calculated from Arrhenius plot and average temperature every 2 hours. As the result of calculating the among ΔP_{cal} obtained using the temperatures on the upper and lower surfaces of the VIP in the room2, the error from

the measured value was smaller in the result calculated by referring to the temperature on the metallized film's side than the aluminum foil's side. This is attributed to the higher temperature dependence of the transmittance of dry air on the metallized film compared to that on the aluminum foil. In the future, we will construct VIPs equipped with micro-pressure sensors in each room and predict the long-term performance based on the comparisons of thermal conductivity, temperature, humidity, and pressure.

Table 4. Installation periods of the different VIPs used in the test of real-world conditions

	Day installed	Day removed	Days after product was manufactured
VIP01	191	34	225
VIP02	191	44	235
VIP03	191	34	225



Fig6: Construction in real environment of VIP

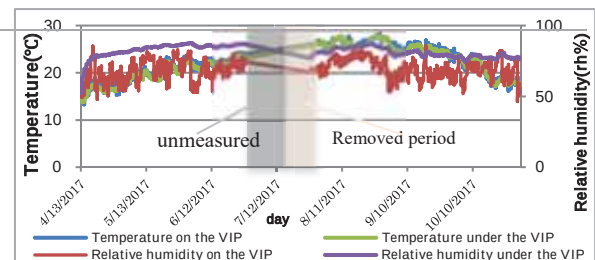


Fig.8. Temperature and relative humidity measured in room 2 on and under the VIP

Place	Matallize d film	Internal pressure (measured, ΔPm)	Reference temperature	Internal pressure (calculated, ΔPcal)	error (%)
Room 1	Upside	10.3	Upside	9.984	3.03
			Lower	9.944	3.42
Room 2	Lower	8.18	Upside	10.331	26.3
			Lower	8.734	6.76
Room 2	Upside	10.74	Upside	10.331	3.78
			Lower	8.734	18.6

Table 5. Comparison of measured and calculated values of internal pressure for each room

5. Conclusion

We developed a micro-pressure sensor and constructed a system that can directly measurement the internal pressure in a real environment. Using this system, the thermal conductivity can be determined without direct measurements. We constructed an Arrhenius plot from the change in the thermal conductivity determined in a laboratory experiments. The transmittance at 35°C and 80% RH was consistent with the Arrhenius plot; however, the

transmittance at 50°C and 70% RH was 6% greater than that at 50°C. We consider that the dependence on the temperature and humidity of the metallized EVOH layer is attributed to it.

We investigated the long-term performance of VIPs on the OA floor of a new building based on the Arrhenius plot obtained in laboratory experiments. We measured the surrounding environmental conditions and calculated the change in internal pressure. The error in the experimental value was smaller when referring to the temperature on the metallized film's side. Because the performance of the metallized film is highly dependent on temperature and humidity, it seems that there was a difference in the time rate of thermal conductivity depending on the direction of construction.

4. Future study

Using VIPs equipped with micro-pressure sensors, we will examine the improvement in accuracy of durability prediction by comparing it with the result of thermal conductivity measurement. We will discuss the relation between external environment and internal pressure. And we will also study the influence of getter material, folded edges on gas permeability calculation, time rate of transmittance due to material deterioration, and another size of VIP.

Acknowledgements

This study was performed in cooperation with everyone at the TODA CORPORATION DEVELOPMENT CENTER. The authors express their sincere thanks.

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Symbols λ_{csp} : thermal conductivity at the center of the panel [W/mK]; λ_s : solid thermal conductivity [W/mK]; λ_g : gaseous thermal conductivity [W/mK]; λ_r : radiative thermal conductivity [W/mK]; M_i : Avogadro's constant [kg/mol]; V_{eff} : volume of VIP [m³]; R : gas constant [J/Kmol]; K_i : mass transfer coefficient [g/h Pa]; $P_{i,atm}$: partial pressure of gas under atmospheric pressure [Pa]; P_i : pressure inside the VIP [Pa]; P_{wv} : water vapor pressure inside the VIP [Pa]; $K_{i,total}$: overall transmittance ($i = a, v$) [g/day Pa]; $K_{i,A}$: transmittance per unit area [g/m² day Pa]; $K_{i,L}$: transmittance per

unit length [g/L day Pa]; A : surface area of VIP [m²], L : Circumference of VIP [m].

Climate Change, Mass Timber, and Biodeterioration – A Synthesis

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Abstract:

Mass timber and Tall Wood buildings represent the leading advancement in sustainable building design using materials that have a significantly reduced environment impact than traditional structural materials. To achieve climate change mitigation targets, the embodied carbon of structures forms a significant component of the overall carbon load in high efficiency buildings. This places engineered wood, an organic material susceptible to biodegradation, in critical structural applications with a greater environmental exposure. To counter this susceptibility, proper moisture management strategies are required. Hygrothermal simulations with biodeterioration post-processing programs appear to be a promising method to quantify, control, and minimize adverse moisture concerns in mass timber buildings.

Keywords:

Climate Change, Embodied Carbon, Tall Wood, Mass Timber, Biodeterioration Modeling

1. Introduction

Advances in low environmental impact buildings are breaking ground in new methods to reduce climate change impacts created by the building industry. With the significant threats to humanity posed by climate change [1], [2], every effort to reduce climate change is required. As buildings are responsible for 6% of direct and 12% of indirect worldwide CO₂ emissions [1], and 40% of CO₂ in North America [3], the Intergovernmental Panel for Climate Change (IPCC) identifies the building sector as one of the most receptive for cost-effective carbon emission reductions [4].

Building related emissions occur in two ways: *embodied carbon* (EC), or *operating carbon* (OC). Embodied carbon is the cumulative emissions associated with the production, provisioning, and construction of the building, normalized to an equivalent CO₂ level (CO_{2eq}). Operating carbon is the carbon equivalent required for the maintenance and operation of the building.

Low-impact buildings, which require highly insulated enclosures, generally find embodied carbon reduction by using mass timber and engineered wood products. Embodied carbon can only be reliably reduced by using carbon sequestering materials, mainly mass timber and other wood products [5], [6]. However, the greater exposure of these primary wood structural elements, caused by taller and larger buildings, pose heightened biodeterioration risk not experienced in conventional structures. Consequently, careful attention to the design and construction process are required and can be assisted with the use of biodeterioration assessment tools.

2. Embodied Effects

Embodied effects are those impacts created as a process in the acquisition of raw materials and

the manufacture, transport, and installation the product in the initial construction of a building [7], termed cradle-to-gate. The effects can include myriad factors such as ozone depletion, eutrophication, energy, and, of primary concern for climate change, embodied carbon [8].

Operating carbon can be reduced through energy conservation measures (ECMs) implemented throughout the service life of the building. These ECMs generally consists of superior thermal resistance of the building enclosure or energy efficient systems (e.g. LED lighting, high COP heat pumps, etc). Critically, embodied carbon can only be affected once, during the initial design and construction of the building. The primary structure and enclosure, represents between 60-90% of initial embodied carbon [8].

Operating energy is generally assumed to form the dominant carbon load of a building, constituting approximately 90% of the total energy load [9]–[11]. The effects of cumulative operating and embodied energy is shown in Figure 1.

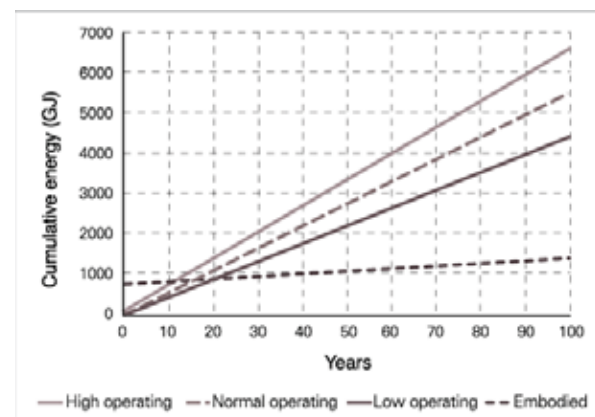


Figure 1 Comparison of embodied to operating energy for a single-family home [12].

The challenge with using *operating energy* instead of *operating carbon* is that energy production is highly sensitive on the emissions factor of the electrical grid system. Table 1 shows the emissions factor to produce electricity in a low-carbon electrical grid (British-Columbia), a carbon intensive grid (Alberta), and a mixed grid (Ontario). The operating emissions intensity ($\text{kgCO}_{2\text{eq}}/\text{m}^2/\text{year}$) can be calculated for 3 building efficiency levels as determined by their energy use intensity (EUI, in $\text{kWh}/\text{m}^2/\text{year}$). An EUI of 75 represents a highly efficient building, whereas an EUI of 300 more closely represent code-minimum.

Table 1 : Electricity Emissions Factor by Select Provinces and Total Building Emissions Intensity for 3 Energy Use Intensity Scenarios, assuming 100% Electricity [13]

Province	Emissions Factor ($\text{g CO}_{2\text{eq}}/\text{kWh}$)	OC Emissions Intensity ($\text{kgCO}_2/\text{m}^2/\text{year}$)		
		Energy Use Intensity ($\text{kWh}/\text{m}^2/\text{year}$)		
		75	150	300
British-Columbia	17	1.3	2.5	5.1
Alberta	820	61.5	123	246
Ontario	80	6	12	24

In a life-cycle analysis, Robertson [8] assesses the embodied carbon for equivalent reinforced concrete and timber frame buildings to be approximately 420 and 126 $\text{kg CO}_{2\text{eq}}/\text{m}^2$, respectively. When combined with EUI, and over an assumed 100 year lifespan, the ratio of embodied carbon to total carbon can be estimated, shown in Table 2.

Table 2 : Ratio of Embodied Carbon to Total Carbon for 3 Building Efficiency Scenarios with Different Emissions Factors for Electrical Production over a 100 year Service Life.

Primary Structure Composition						
Province	Reinforced Concrete			Mass Timber		
	EUI (kWh/m2/year)					
	75	150	300	75	150	300
BC	76%	63%	45%	49%	34%	20%
AB	6%	3%	2%	2%	1%	1%
ON	41%	26%	15%	17%	10%	5%

Table 2 shows that high-efficiency buildings in low emissions factor provinces are highly sensitive to the embodied carbon of the structure. A concrete framed structure can represent 76% of the total emissions of a building to embodied carbon, whereas this value decreases to 49% in a wood-frame equivalent structure. Consequently, the importance of embodied carbon in high efficiency buildings in low

carbon intensive electrical grid systems cannot be understated.

3. Mass Timber Challenges

Despite the advantages of mass timber and tall wood in reducing global warming concerns, preservation of this sequestered carbon is essential and poses unique challenges. As an organic material, wood is susceptible to biodegradation by multiple agents, decay being the single greatest durability concern (Zabel & Morrell, 1992). The risks associated with biodeterioration are a function of exposure to environmental loads and the consequence of failure. Both factors are significantly increased in tall wood structures, as the environmental exposure to moisture loads are heightened and the consequences of primary structural failure can be catastrophic.

4. Causes of Decay

The onset of decay can only occur given concurrency of six main factors. 1) Moisture ($>25\%MC$), 2) Temperature ($5^\circ\text{C} < T < 35^\circ\text{C}$), 3) Suitable substrate with sufficient nutrient density and chemical growth factors and pH, 4) Oxygen ($>3\%\text{O}_2$), 5) Minimal antagonistic effects, and 6) Sufficient time for growth (3+ months, depending on conditions) [14]–[16]. Elimination of any of these items will prevent decay.

Occupant thermal comfort and environmental climate norms limit temperature as a controlling variable, and the substrate (mass timber) is designated. The pervasiveness of oxygen prohibits its use to control decay, and while biocides can be an option, these exhibits reducing efficacy with time, increased production costs, and may have potential health effects for some occupants. This leaves moisture as the main variable to be controlled.

Moisture is present in the building environment in 4 different phases (gas, liquid, solid, and adsorbed) and from 4 main sources [17], listed in approximate order of magnitude:

- Bulk water: caused by precipitation or plumbing leaks
- Construction moisture: built-in moisture absorbed by materials during construction
- Air leakage: condensation formed when humid air contacts a cold surface
- Water Vapour: vapour diffusion flow from high concentration to low

Proper design can minimize many of these moisture sources and thus significantly reduce the risk associated with biodeterioration. However, complete elimination of these sources is impossible, and thus quantifying limiting thresholds to infer long-term durability is necessary.

5. Mitigation and Biodeterioration Modeling

A hierarchy of controls concept can be used when designing for moisture-resilient buildings. Methods to decrease the impacts of biodeterioration on organic structures comprise one of three methods:

- 1) Elimination: avoidance schemes involve shielding the material from possible deterioration mechanisms. This could include minimizing water content during construction, or designing wall assemblies to dry. The 3-D concept of moisture management (deflect, drain, and dry) consists of an elimination approach
- 2) Protection: protection approaches do not try to stop the environmental circumstances which could cause biodeterioration, but attempt to stop the decay agents from creating any damage to the structure.
- 3) Symptom Management: the symptom management approach tries neither to avoid biodeterioration nor protect the material from the decay mechanisms, but rather attempts to resolve symptoms, such as through maintenance and repairs.

In a case study of a tall wood building in Vancouver, it was found that a combination of the three response methods was required to adequately address biodeterioration risks to the primary structure, secondary structural elements, and wood-based exterior finishes [18].

Evaluating anticipated moisture loads on buildings has taken multiple approaches, from the Scheffer Index [19], the Moisture Index [20], the RHT index [21]. More recently, combined heat and moisture flow simulation software, such as WUFI Pro®, permit hourly assessments of moisture loads on building assemblies. The output from these hygrothermal models generally consists of the material moisture content or equilibrium relative humidity. The challenge is in extending these intrinsic material properties to infer durability; biodeterioration models can assist in this assessments. Detailed summaries of many of these models are provided by Vereecken [22] and Lepage (2018), and hold promise to provide realistic, long-term durability assessments of the built environment.

6. Conclusions

Mitigating climate change impacts through careful consideration of embodied energy of building is a necessary approach for high-performance buildings in low emissions factor grid systems. This is mainly achieved by the careful use of mass timber and engineered wood products to provide primary structural support. However, the increased environmental exposure and the more critical structural functions performed by wood increase the risk from decay, an unfortunate susceptibility to all organic materials. Despite this predisposition, moisture management strategies can be deployed to mitigate the risk. Biodeterioration models, a more advanced approach to assess moisture durability risk, are promising alternative to traditional methods, thus helping preserve the embodied carbon within the building structure.

Acknowledgements

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Application of Fly ash and Bottom Ash Based Alkali Activated Concrete Paver Blocks for Design and Construction of Rural Pavements

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Abstract:

Paver blocks used in construction industry utilizes Portland cement as a binder which contributes tons of the greenhouse gas emissions every year. Hence, it is essential to discover alternative binder to make an environment friendly concrete paver blocks to use in the pavement. An attempt has been made herewith to investigate feasibility of alkali activated concrete paver blocks for application in rural pavement having low traffic volume. The rural pavement contained fly ash and bottom ash based alkali activated concrete paver blocks. Traffic analysis is carried out to finalize traffic category, minimum thickness and minimum grade of paver blocks required during the construction of a rural pavement. Alkali activated concrete paver blocks of required grade and thickness are manufactured, tested for mechanical properties like compressive strength and breaking load & used in the construction of rural pavement. The said paver blocks also sufficed the compressive strength and breaking load requirements as per IS 15658 [1] for low volume traffic category. It is observed that both compressive and breaking load of ambient cured alkali activated paver block was superior to commercially available paver block. A rural pavement of size 2.5 m × 16 m is constructed using the same paver blocks at Jaspur village, Ta. Kalol, District. Ahmedabad, Gujarat, India. Performance of the said pavement has been monitored. No damage is observed through visual observation after 5 months of construction of rural pavement.

Keywords:

Fly ash, Bottom ash, Alkali activated concrete, Paver block, Rural pavement

1. Introduction

Now a days, due to lower service life and number of geological, traffic, environmental and operational constraints, bituminous pavement has not been much used. On the other hand, interlocking concrete paver block pavement has been broadly used all over the world because of its advantages like less maintenance, good drainage, less usage of machineries, less requirement of labors & time for opening to the traffic. Hence, it is advisable to use interlocking paver blocks for making the rural pavement. For making interlocking concrete blocks, construction industry uses Portland cement as a binder which contributes tons of CO₂ emission every year. Hence, it is imminent to discover alternative binder which have almost same mechanical & durability properties like conventional concrete to make environment friendly concrete paver blocks [2].

On the other hand, huge quantities of fly ash and bottom ash are generated around the globe from thermal power plants and industries have major problem of disposal of these by products. Fly ash has found lot of application as replacement of cement, bottom ash is still not being effectively used and is generally disposed as landfill causing immense problem related to land, soil and underground water

pollution. Therefore, it is necessary to use these byproducts in meaningful manner.

One of the alternative is alkali activated concrete. The said concrete utilizes poly-condensation process to achieve the required strength. The concrete made up using this byproducts like fly ash and bottom ash are activated by alkaline medium to produce an inorganic polymeric binder known as alkali activated concrete [3].

One of the disadvantage of alkali activated concrete is that it requires heat for polymerization process. The alkali activated concrete paver blocks produced without using elevated heat for curing will widen its application in precast industries [4].

In this study, it is aimed to make fly ash and bottom ash based alkali activated concrete paver blocks cured at ambient temperature for application in rural pavement having light traffic volume.

Alkali activated concrete block pavements consists of a layer of alkali activated concrete paver blocks paved on a thin, compacted bedding sand layer having specified grade. The said pavement is constructed over a properly profiled base course and is bounded by edge restraints / kerb stones.

Thereafter, joints between the blocks are filled using fine material & blocks are embedded in to sand bedding using compactor [5].

2. Grade and Thickness of Paver Block for using in Pavement

Traffic analysis of rural pavement is carried out to find number of vehicles passed during a day. From the number of vehicles, cumulative number of standard axles is found out which is subsequently used to define the traffic category as per provisions of IS 15658[1]. Based on the traffic category, the required grade, minimum thickness of paver blocks to be used for the proposed rural pavement is worked out.

The Design traffic is considered in terms of the cumulative number of standard axles. In rural pavement at Jaspur village, Ta. Kalol, District. Ahmedabad in Gujarat state, maximum axle vehicles are trucks/buses and four wheeler cars. Hence, for finding out cumulative standard axles (CSA), sum of cumulative standard axles for four wheeler vehicles (CSA₁) and cumulative standard axles for truck/buses (CSA₂) are carried out. This is calculated as per IRC 37 [6] using Equation 1,

$$N = \frac{365 \times [(1+r)^n - 1]}{r} \times A \times D \times F \quad (1)$$

Where,

N = The cumulative number of standard axles in terms of msa (million standard axles)

A = Initial traffic in the year of completion of construction in terms of the number of commercial vehicles per day (Finalized based on traffic survey)

D = Lane Distribution factor as per IRC 37 [9] = 1 (For single carriageway),

F = (Axle load of vehicle / standard axle load which taken as 8160 kg)⁴

n = Design life in years = 15 years (Assumed)

r = Annual growth rate of vehicles = 7.5 %

Calculation of cumulative standard axles for four wheeler vehicles :-

A = No. of four wheelers per day = 226

Axle weight of four wheelers = 2610 kg (Assumed)

F = (2610/8160)⁴ = 0.0104

From the above values, cumulative number of standard axles for four wheelers is found out,

$$N = \frac{365 \times [(1+0.075)^{15} - 1]}{0.075} \times 226 \times 1 \times 0.0104$$

CSA₁ = 0.0227 msa

Calculation of cumulative standard axles for Truck/Buses vehicles:-

A = Number of Vehicles per day = 38

Axle weight of truck/buses is taken as 8160 kg

F = (8160/8160)⁴ = 1

From the above values, cumulative number of standard axles for trucks/buses is found out,

$$N = \frac{365 \times [(1+0.075)^{15} - 1]}{0.075} \times 38 \times 1 \times 1$$

CSA₂ = 0.362 msa

Total CSA = CSA₁ + CSA₂
= 0.0227 + 0.362
= 0.3847 ≤ 0.5 msa

(For light traffic category as per IS 15658 [1])

So, the proposed rural pavement is under low traffic category as per IS 15658 [1]. For light traffic category, as per IS 15658 [1] minimum grade of paver block required is M 35 & minimum thickness of paver blocks required is 60 mm. Hence target strength of M 35 and thickness of 60 mm is taken for construction of paver blocks.

3. Manufacturing Process of Alkali Activated Concrete Paver Blocks

3.1 Preparation of Alkaline Solution

Alkaline solution consists of sodium hydroxide (NaOH) & sodium silicate (Na₂SiO₃). Sodium hydroxide solution is made up by dissolving sodium hydroxide flakes in water. The mass of NaOH solids in a solution varies depending on the concentration of the solution required which is expressed in terms of molar, M. The mass of NaOH solids is measured as 255 grams and 745 grams water is added for 1 kg of NaOH solution of 8M concentration [7]. After cooling down, sodium silicate is mixed with sodium hydroxide solution as per the ratio of alkaline solution ratio.

3.2 Casting and Curing of Alkali Activated Concrete Paver Blocks

Alkali activated paver blocks is manufactured using rubber moulds of Zigzag / Unipaver shape of 60 mm thickness as shown in Figure 1. The mixing procedure for alkali activated paver blocks is similar to that of conventional cement concrete paver blocks. Properties of fly ash and bottom ash used are as per IS 3813 [8]. The properties of aggregates are found as per IS 2386 [9] and IS 383 [10]. The fly ash, bottom ash and the aggregate has been mixed together in pan mixture. The mixing is allowed to continue for

about 3 to 4 minutes. The alkaline solution which is prepared one day before is added with additional water in the mix and mixing is continued for another 3 to 4 minutes. The fresh alkali activated binders is cast into the moulds immediately after mixing in three layers. For compaction of the specimens, each layer is given 25 to 35 manual strokes using 20 mm rod. Specimens are vibrated using vibration table for another 10 to 15 seconds. After compaction of the specimen, the top surface is leveled by using trowel and also the sides of mould are struck by using hammer in order to expel air if any present inside the concrete and to make the sides smoothened [11]. After the casting, the specimens have been kept at room temperature as per the designated rest period. Setting of fresh alkali activated paver blocks is as shown in Fig 2. Ambient curing has been used for all the specimen in the present study in which temperature ranges from 25°C to 30°C. In ambient curing, the specimens are left in open atmosphere for curing period till testing time [12].



Figure-1: Rubber mould of Zigzag / Unipaver shape paver block



Figure 2: Alkali activated concrete paver blocks at rest period

4. Mechanical Properties of Alkali Activated Paver blocks

Compressive strength and breaking load of commercially available and alkali activated paver block is evaluated and compared.

4.1 Compressive Strength

Compressive strength of alkali activated paver blocks and commercially available cement concrete paver blocks are evaluated as per IS 15658 [1] at age of 7 days and 28 days. Average of four paver blocks are considered as average compressive strength of paver blocks. The corrected compressive strength shall be calculated by multiplying the apparent compressive strength by the appropriate correction factor for thickness and chamfer curved edge from Table 5 of IS 15658 [1]. At 7 and 28 days the average compressive strength of commercially available paver blocks is 27.91 MPa and 36.62 MPa while alkali activated paver blocks has a strength of 34.21 MPa and 42.95 MPa. Thus, both paver block exhibited higher compressive strength at 28 days than that required for M 35 grade for light volume traffic as per IS 15568 [1]. Also alkali activated concrete paver blocks have higher compressive strength at both 7 and 28 days when compared with cement concrete paver blocks.

4.2 Breaking Load

The breaking load at an age of 7 and 28 days is evaluated for alkali activated paver blocks & commercially available paver blocks according to IS 15658 [1]. Average of four paver blocks are considered as average breaking load and for commercially available paver block breaking strength is observed as 3.86 MPa and 6.83 MPa at 7 and 28 days respectively while for alkali activated paver block it is 6.14 MPa and 8.33 MPa for 7 days and 28 days. Alkali activated concrete paver blocks attained the breaking load of 8 kN which is significantly higher than the breaking load required for driveways having low volume traffic of 5 kN at 28 days. The said paver blocks are further capable for industrial/heavy duty roads for which the requirement of breaking load is of 7 kN.

5. Construction of Rural Pavement

5.1 Plan & Cross Section

Plan & Section of Rural Pavement constructed at Jaspur Village is given in Figure 3.

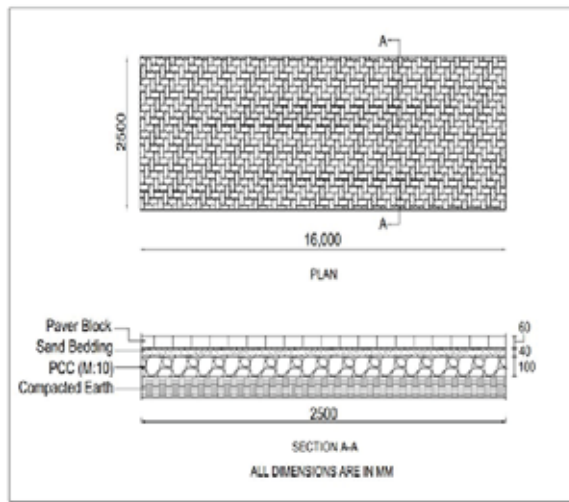


Figure 3: Plan & Section of Rural Pavement

5.2 Construction Process

The step-by-step procedure employed for making the rural pavement is as follows:

5.2.1 Preparation of Paver Blocks:-

1200 Nos. of alkali activated concrete paver blocks having grade of M35 are casted at concrete casting yard of Nirma University, Ahmedabad and cured at ambient temperature (temperature between 25°C to 30°C) as shown in Figure 4.



Figure 4: Casting of alkali activated concrete paver blocks

5.2.2 Marking and Excavation

Figure 5 represents excavation process of the rural pavement using backhoe of size 2.5 m × 16 m having depth of 200 mm.



Figure 5:Excavation of 200 mm depth using backhoe

5.2.3 Levelling & Compacting

After excavation, the surface of earth is levelled and compacted with the help of tamper as presented in Figure 6.



Figure 6: Levelling & Compaction of Earth using Tamper

5.2.4 Transportation & Storage of Paver Blocks

Alkali activated concrete paver blocks are transported from Nirma University to Jaspur village & stored at the site with the help of local transport agency as shown in Figure 7.



Figure 7: Storage of paver blocks

5.2.5 Laying of Kerb Stones

After Levelling and compaction of earth, edges of pavement are restrained using edge restraints like kerb stones. Locally available kerb stones having depth of 12 inch are used. Laying of kerb stones is employed which is presented in Figure 8.



Figure 8: Laying of 12 inch kerb stones

5.2.6 Laying of Base Layer

After completing kerbing around the periphery, 100 mm thick Portland cement concrete layer having grade of M 10 is cast. Mixing is done manually as shown in Figure 9. Laying & levelling of concrete layer is carried out which is presented in Figure 10.



Figure 9: Preparation of M10 grade concrete



Figure 10: Laying of Portland cement concrete

5.2.7 Laying of Sand Bedding

After laying of PCC, laying of sand bedding having depth of 40 mm is carried out which is presented in Figure 11. 4.75 mm passing sand is used for sand bedding.



Figure 11: Laying of 40 mm Sand Bedding & Levelling

5.2.8 Laying of Paver Blocks

After laying and levelling of sand bedding, around 1200 numbers of alkali activated concrete paver blocks are laid in herringbone pattern as shown in Figure 12. After laying of paver blocks, edges are filled with cement mortar which is presented in Figure 13.



Figure 12: Laying of pavers in herringbone pattern



Figure 13: Mortar filling near edges

5.2.9 Joint Sealing & Compaction

After laying of paver blocks, the space between paver blocks are filled with the help of joint sealing sand. 2.36 mm passing sand is used for joint sealing of paver blocks. Thereafter, vibrator is used for compacting of paver blocks as presented in Figure 14.



Figure 14: Compaction on paver blocks

5.2.10 Rural Pavement of Alkali Activated Concrete Paver Blocks

The view of alkali activated concrete paver block pavement constructed at Jaspur village, Ta. Kalol, District. Gandhinagar, State. Gujarat is shown in Figure 15.



Figure 15: Rural pavement at Jaspur village

6. Monitoring of Rural Pavement

Visual inspection of the rural pavement has been done at the interval of every month since last five months after completion of construction of the pavement in April-2017. The paver blocks have been observed for any cracks as well as any deformation. No cracks or any type of settlement of any of the paver blocks has been observed till date. However, it has been planned for long term study of the performance of the paver blocks for the time duration of about twelve months. In the said context, it has been planned to evaluate the difference in compressive strength, breaking load & leachate test of alkali activated concrete paver blocks at the time interval of 6 months & completion of 1 year, respectively. Few selected paver blocks will be replaced from the pavement & tested in the laboratory for the above mentioned properties. New paver blocks will be in-stalled at the places on the pavement from where the original paver blocks are replaced for the testing.

7. Conclusion

Based on the experimental results of mechanical properties and design and the construction of rural pavement presented herewith the following conclusions are drawn:

1. Ambient cured alkali activated concrete paver blocks exhibited superior compressive strength compared to that of commercial paver blocks.
2. Ambient cured alkali activated concrete paver blocks have superior breaking strength compared to commercial paver blocks.
3. Alkali activated concrete paver blocks developed herewith have been able to give better results as compared to the requirement of minimum compressive strength as suggested by IS 15658 [1] for light traffic category.
4. No damage is observed during visual observation on the alkali activated concrete paver blocks rural pavement even after five months to the development of the said pavement.
5. Alkali activated concrete paver blocks pavement can be effectively use in the construction of rural pavement.

Acknowledgement

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Future weather files to support climate resilient building design in Vancouver

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Abstract:

Since local weather and climate greatly affect the construction and performance of buildings, reliable meteorological data is essential when simulating building performance. It is well understood that climate change will affect future weather and there is a growing interest in generating future weather files to support climate resilient building design. Weather files that account for climate change have not been widely used for the lower mainland region of British Columbia. In this study, hourly weather files for future climate conditions in Vancouver are created for three time periods using a “morphing” methodology. Morphing uses results from global climate models to adjust observed weather data at a specific location. In this study, daily data from climate simulations for the RCP8.5 emission scenario have been used. The weather variables that have been adjusted are dry-bulb temperature, relative humidity, solar radiation, cloud cover, wind speed and atmospheric pressure. The impact of climate change on the energy performance of a multi-unit residential building located on the University of BC campus is analyzed using the energy modelling software EnergyPlus. The simulation results indicate that the changing climate in Vancouver, following RCP8.5, would have a considerable effect on building energy performance and energy demand due to decrease in space heating and increase in cooling requirements.

Keywords:

Weather File, Climate Change, Energy Modelling, Building Simulation, Downscaling

1. Introduction

Dynamic building simulation is an important tool in analyzing the energy performance of building design options. The performance of building envelopes as well as heating and cooling systems are greatly affected by local climate. Therefore, reliable meteorological data is essential when simulating building performance to achieve energy efficient and comfortable buildings. It is well understood that climate change will affect future weather [1]. Since typical building lifetimes can be around 60 years or more, weather files need to cover projected future changes [2]. This has been acknowledged globally and there is a growing interest in using weather files that account for climate change [2-6].

The impact of climate change on energy use patterns in the building sector is poorly understood in the lower mainland region of British Columbia. In this study, hourly weather files for future climate conditions are produced to investigate potential implications for building energy performance in Vancouver.

This project was initiated by the University of British Columbia (UBC) Sustainability and Engineering and was carried out in conjunction with two main project partners: Pacific Climate Impact Consortium (PCIC) and RDH Building Science.

2. Methodology

Several methods can be used to construct weather files for building simulation [1,2]. As a first step, the methodology in this study is based on the work by Belcher et al. [3], referred to as morphing. The concept behind morphing is to generate weather files that account for future climate changes by adjusting historical observations with results from simulations made with global and/or regional climate models.

The morphing methodology has been widely used to predict the impact of climate change on building performance [7-11]. A key reason often cited is because it allows for spatial and temporal downscaling using site-specific weather data so that future projections can be generated that preserve the characteristics of the weather for the specific station. This feature may also have some unintended consequences [12]. In this study, implementation of morphing is considered a first step in producing future weather files, with considerable avenues of further work to investigate (see Conclusions).

The scope of this preliminary investigation was to apply morphing techniques that have been used elsewhere, with only one modification (using daily rather than monthly climate projections). It was beyond the scope of this first step to evaluate the morphing operations used for each parameter and the implications that different choices would have. However, this is an

important aspect to evaluate. Several recommendations for further research are provided in the conclusions.

2.1 Climate Change Correction

The first step in the morphing procedure is to create baselines that represent current and future climate. Baselines consist of climate data for each day of the year and are defined by taking the average of climate simulations over a 30-year period [13].

Daily simulations for the parameters (see Table 2) were available from eight global climate models (GCMs). These GCMs are listed in Table 1.

Table 1: The global climate models used to simulate present-day and future climate baselines.

Global Climate Model
CNRM-CM5
CanESM2
ACCESS1-0
Inmcm4
MIROC5
GFDL-ESM3g
MRI-CGCM3
GFDL-ESM3G

Daily climate projections for the simulation period 1950-2100 were provided by Pacific Climate Impact Consortium (PCIC). For temperature and precipitation PCIC offers statistically downscaled climate data for Canada. Data from GCMs were downscaled to a gridded resolution of roughly 10 km by using Bias-Correction/Constructed Analogues with Quantile mapping reordering (BCCAQ) [14]. For the rest of the weather variables (see Table 2) climate data were provided by PCIC with a gridded resolution of roughly 100 km.

In this study, simulations under the assumption of the RCP8.5 emission scenario are used. In 2014 the IPCC finalized the fifth Assessment Report (AR5) which includes four greenhouse gas concentration pathways, the so called Representative Concentration Pathways (RCPs). These scenarios describe possible climate futures depending on how much greenhouse gases that are emitted in the years to come. The RCP8.5 scenario roughly reflects a 'business as usual' scenario [15].

To define the present-day climate baseline, simulations for the time period 1971-2000 are used. Three future time periods are studied: centred on 2020s, 2050s and 2080s (i.e., 2011-2040, 2041-2070, 2071-2100).

When the present-day and future climate baselines are defined the climate 'correction factors' can be determined. The 'correction factors' represent the change in the daily mean value for each variable.

The remaining section is following the convention of Belcher et al [3]:

The absolute change between the future and present-day baseline for day d is called 'shift factor', Δx_d , and is calculated by equation 1.

$$\Delta x_d = \langle x_{future} \rangle_d - \langle x_{present} \rangle_d \quad (1)$$

The fractional change between the future and present-day baseline for day d is called 'stretch factor', α_d , and is calculated by equation 2.

$$\alpha_d = \frac{\langle x_{future} \rangle_d}{\langle x_{present} \rangle_d} \quad (2)$$

Unlike the previously mentioned studies [7-11] in which monthly climate projections were used to create future weather files, the climate projections used in this study are daily time series.

2.2 Morphing operation

After the climate correction factors are generated, the next step is to adjust observed data. This is achieved by creating algorithms where a function of the difference between the climate baselines is applied to the existing data. These algorithms are based on three different operations, following Belcher et al., equation 3-5 demonstrate the operations. Note that these methods include an estimation of change in diurnal cycle because they were designed for use with monthly climate projections. The next step in this work is to re-evaluate which variables are shifted, stretched, or both – and if some variables should not be adjusted at all (see conclusions). The choice of which changes were applied to which variables in this initial investigation follows the conventions of Belcher et al. (see section 2.3 and Table 2).

Shift

$$x = x_0 + \Delta x_d \quad (3)$$

x : future hourly weather variable

x_0 : hourly observed weather variable

Δx_d : shift factor, predicted absolute change in the daily mean value of the variable for day d

The shift operation adds the projected absolute change obtained from climate model simulations and as a result the observed weather data for a given day is shifted by Δx_d . The daily variance of the variable remains unchanged. The new daily mean value of the variable is $\langle x \rangle_d = \langle x_0 \rangle_d + \Delta x_d$, where $\langle x_0 \rangle_d$ is the observed present-day daily mean value of the variable, x_0 , for day d .

Stretch

$$x = \alpha_d x_0 \quad (4)$$

α_d : stretch factor, predicted fractional change in the daily value of the variable for day d

The stretch operation multiplies the observed weather data by the predicted fractional change obtained from climate model simulations. As a result, the observed weather data is scaled with α_d . This operation changes the daily mean and variance of the future weather variable. The daily mean value becomes $\langle x \rangle_d = \alpha_d \langle x_0 \rangle_d$ and the daily variance becomes $\langle \sigma^2 \rangle_d = \alpha_d^2 \langle \sigma_0^2 \rangle_d$, where $\langle \sigma_0^2 \rangle_d$ is the daily variance of the observed weather data for day d .

Combination of shift and stretch

$$x = x_0 + \Delta x_d + \alpha_d \times (x_0 - \langle x_0 \rangle_d) \quad (5)$$

The third operation is a combination of a shift and a stretch. The current hourly weather data is shifted by adding the predicted absolute change and stretched by a predicted diurnal ratio of the variable. This approach is applied when both the mean and variance of the variable is changed. This operation results in a change in the daily mean value and variance of the future weather variable. The new mean value is $\langle x \rangle_d = \langle x_0 \rangle_d + \Delta x_d$ and the new daily variance is $\langle \sigma^2 \rangle_d = \alpha_d^2 \langle \sigma_0^2 \rangle_d$.

2.3 Current and future weather files for Vancouver

In North America, the most commonly used weather file for building energy performance simulations is called Typical Meteorological Year (TMY) [16]. A TMY file represents the typical long-term weather pattern and is created by analyzing 15-30 years of historical hourly data for the specific site [17].

In this study, the open-source software EnergyPlus is used as the simulation tool. EnergyPlus provides weather files in the TMY format for cities around the world, commonly referred to as 'EnergyPlus/ESP-r Weather' (EPW). The EPW file currently used in EnergyPlus for Vancouver is based on observed data from YVR for the time period 1960-1985 [18]. It was decided that the most suitable approach was to

develop climate change adapted TMY files and to provide them as EPW files.

In this study, the EPW file for Vancouver is morphed. Table 2 summarizes the weather variables that are adjusted, together with the required projected climate variables and the algorithm used to generate future data. For each variable, an algorithm has been designed in Matlab to suit the format of the climate data. The choice of morphing algorithm for each variable is presented below, following the work by Belcher et al. [3].

Dry Bulb Temperature (°C)

The methodology proposes to change the mean and the variance of the existing dry bulb temperature (daily mean surface temperature). This is achieved by the third morphing operation, a combination of a shift and a stretch.

Relative humidity (%)

Following Belcher et al. a stretch operation is applied to calculate the morphed relative humidity. The change between the climate baselines is therefore calculated as a fractional change.

Atmospheric Pressure (Pa)

The climate models provide daily values for sea level pressure. The change in the atmospheric pressure is assumed to be the same as the change in sea level pressure. A shift factor calculated based on the change in sea level pressure is applied to the observed atmospheric pressure to compute the future atmospheric pressure.

Global horizontal radiation (Wh/m²)

The global horizontal radiation is the total amount of direct and diffuse solar radiation received on a horizontal surface. For the global horizontal radiation, it is recommended to stretch the observed data. The stretch operation had to be adopted to avoid the operation resulting in irradiance at night.

Direct normal radiation (Wh/m²)

The direct normal radiation is the amount of solar radiation received directly from the solar disk on a surface perpendicular to the sun's rays. Climate model simulations for direct normal radiation are not readily available. Therefore, an indirect method is applied. It is assumed that the distribution between direct and diffuse radiation is unchanged. The direct normal radiation can be calculated using the generated future data for global and diffuse horizontal radiation.

Table 2 : Morphed EPW weather variables along with climate projection parameters and an overview of the methodology used to generate future weather data

EPW node	EPW weather variable (unit)	Climate projection parameter (unit)	Methodology for future weather data generation
N6	Dry bulb temperature (°C)	tasmin: minimum air temperature tasmax: maximum air temperature (all °C)	Combined shift and stretch using tasmin, tasmax and calculated predicted mean temperature (°C)
N8	Relative humidity (%)	rhs: relative humidity	Stretch of EPW data using rhs
N9	Atmospheric pressure (Pa)	psl: air pressure at sea level (Pa)	Shift of EPW data using psl
N13	Global horizontal radiation (Wh/m ²)	rsds: surface downwelling shortwave (W/m ²)	Stretch of EPW data using rsds
N14	Direct normal radiation (Wh/m ²)	-	Calculated by assuming that the relationship between N13, N14 and N15 remains the same
N15	Diffuse horizontal radiation (Wh/m ²)	-	Stretch of EPW data using the same stretch factor as for N13
N21	Wind speed (m/s)	uas: eastward wind (m/s) vas: northward wind (m/s)	Stretch of EPW data using the magnitude of the two vectors
N22	Total sky cover (tenths of sky)	clt: cloud area fraction (%)	Shift of EPW data using clt

Diffuse horizontal radiation (Wh/m²)

As with direct normal radiation, climate data is not available for diffuse horizontal radiation. It is assumed that the change in diffuse horizontal radiation is proportional to the change in global horizontal radiation. The observed data for diffuse horizontal radiation is morphed using the calculated scaling factor for global horizontal radiation.

Wind speed (m/s)

The wind speed data series is calculated by applying a shift operation to the observed data,

Total cloud cover (tenths of sky)

Following Belcher et al. a stretch operation is applied to calculate the morphed cloud cover. The change between the baselines is therefore calculated as a fractional change.

2.4 Impact of climate change on building energy performance in Vancouver

The future hourly weather data for each scenario is compiled and formatted into EPW files using the software tool Elements [19]. To understand the potential impact of climate change on building energy use in Vancouver, the generated weather files are used to carry out an initial energy analysis.

In this study, the energy performance of a typical high-rise under current building code in Vancouver, located on the UBC campus, is simulated. The archetype was designed by RDH Building Science, as part of a project where building designs were explored to support development of UBC's green building strategy. The archetype consists of a 22-storey multi-unit residential building and sixteen 2-storey townhouses. The archetype includes a mechanical cooling system and is connected to UBC's district heating system. The total floor area of the building is approximately 26 600 m² [20].

The model was run with the EPW currently provided in EnergyPlus, and with the weather files created using the morphing process. The future building energy performance was simulated under the assumption that no technological advances are going to take place.

3. Results and discussions

Table 3 shows the annual mean value of each morphed weather variable. The results indicate that dry-bulb temperature and relative humidity are the variables that will experience the most change.

Table 3: Annual mean value of the morphed weather data

Weather Variable	Present-day	2020s	2050s	2080s
Dry-bulb temperature (°C)	9.7	11.1	12.4	14.1
Relative humidity (%)	60.3	79.5	79.2	79.1
Atmospheric pressure (kPa)	101.6	101.6	101.6	101.6
Global horizontal radiation (Wh/m ²)	140.4	140.8	141.7	142.9
Direct normal radiation (Wh/m ²)	147.1	155.4	155.3	154.0
Diffuse horizontal radiation (Wh/m ²)	59.6	59.8	60.2	60.9
Wind speed (m/s)	3.35	3.39	3.46	3.47
Total sky cover (tenths of sky)	6.75	6.75	6.74	6.72

Figure 1 and 2 below demonstrate the morphing process on dry-bulb temperature. Figure 1 shows the simulated shift factors for dry-bulb temperature for each time scenario.

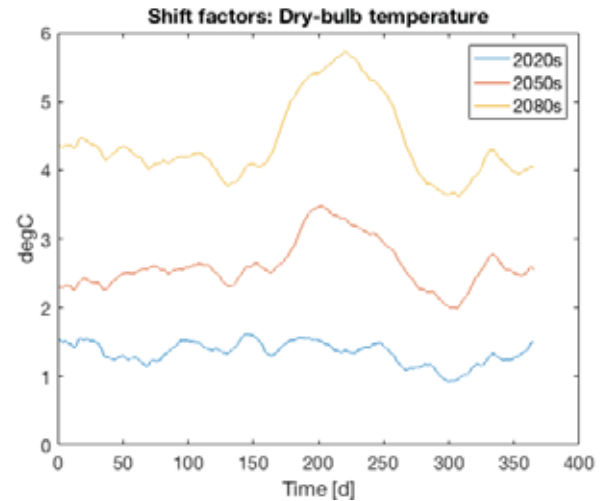


Figure 1: Shift factors for dry-bulb temperature for each time scenario from 8 BCCAQ downscaled GCMs

Figure 2 shows the final climate change adjusted hourly data for dry-bulb temperature under four days in May, together with data from the EPW file for the same time period.

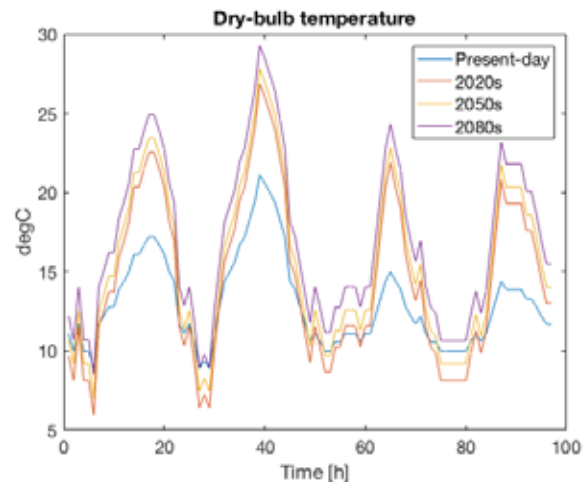


Figure 2: Climate change adjusted hourly data for dry-bulb temperature together with EPW data for four selected days

Figure 3 shows the mean monthly dry-bulb temperature for each weather file.

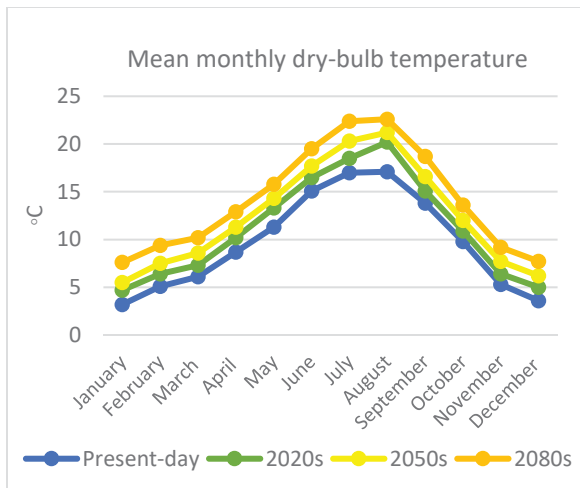


Figure 3: Mean monthly dry-bulb temperature for each weather file

Figure 4 shows the daily standard deviation for dry-bulb temperature, for all four weather files. Note that all sub-daily variability comes from the historical hourly data in the weather files. The standard deviation for dry-bulb temperature is higher for the generated weather files than for the observed weather file. This is due to the use of shift and stretch and indicates that for the predicted future dry-bulb temperature there is a larger variance from the daily mean value. This suggests that application of both a shift and stretch to temperature when using daily climate simulations amplifies the change in diurnal cycle. The effect on the present results is likely an underestimation of the reduction in heating (note in Figure 2 how the stretch causes colder days than present to occur in the coldest hours of the day), and likely an overestimation of the increase in cooling.

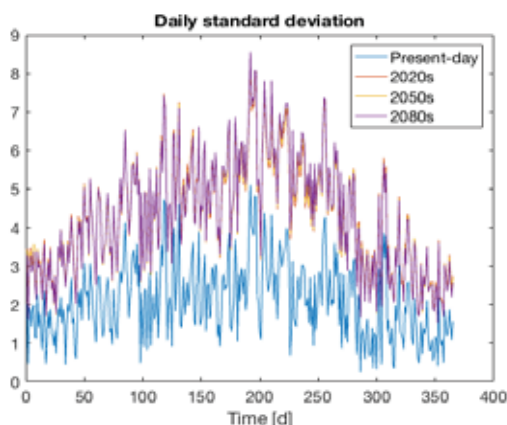


Figure 4: Daily standard deviation for temperature from each weather file

Findings from the building energy analysis are presented below. Figure 5 shows the monthly space heating load for each time scenario.

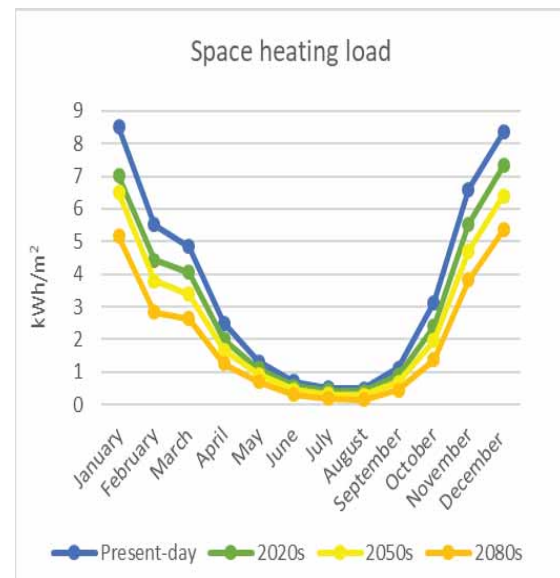


Figure 5: Monthly space heating load for each time scenario

Figure 6 shows the cooling load for each time scenario.

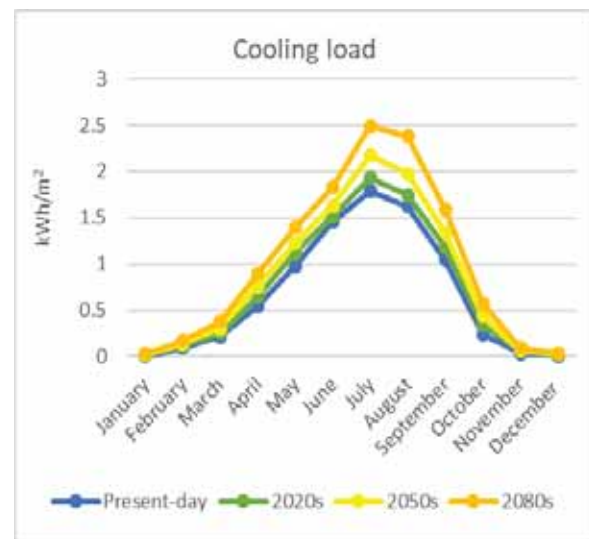


Figure 6: Monthly cooling load for each time scenario

Table 4 shows the percent change in electricity and district heating demand for each time scenario, compared to the results given when using the present-day EPW file.

Table 4: Percent change for electricity and district heating demand for each time scenario

	2020s	2050s	2080s
Electricity			
Cooling	16%	31%	54%
Pumps	5%	10%	17%
Heat Rejection	8%	15%	25%
Total Electricity Demand	2%	4%	6%
District Heating			
Heating	-15%	-27%	-43%
Total District Heating Demand	-10%	-18%	-28%
Total Energy Demand	-3%	-6%	-9%

The findings in this research project indicate that the total energy demand for the studied archetype will slightly decrease with time. The demand for space heating is expected to decline with time and the cooling load to increase with time. For UBC, this means a reduced dependency on district heating (natural gas) and a higher electrical demand. This would have a positive effect on UBC's greenhouse gas (GHG) emissions. However, an increase in electricity load during cooling season is going to exert a greater pressure on the electricity grid. This may result in failure in the power grid and in turn lead to a need to purchase electricity, which may not be GHG neutral.

4. Conclusions and outlook

In this study, weather data in the EPW file currently used in EnergyPlus is adjusted for climate change. The EPW file is in the TMY format, which captures typical weather conditions at a specific site. However, TMY files by design represent "typical" (median) conditions and thus will not include extreme weather events. It is likely that extreme weather events will become more common in the future as a result of climate change. Designing buildings for typical conditions could lead to future vulnerability. To allow designers and engineers to stress test building performance and adapt building design for atypical conditions further research is recommended to focus on creating weather files that

represent hotter than average conditions, including extreme events.

Further, a set of raw data for a specific weather station, where each year is different from the previous one could be morphed. This would offer an alternative to the traditionally used TMY file which would allow to assess the impact of climate change on building design options while introducing year-to-year variability.

Morphing is a class of bias corrections which can have unintended effects on results [12]. The next step in using morphing of weather files on a wider basis is to systematically evaluate the consequences of choices of whether to use shift, stretch, or both for each parameter, and indeed whether to make use of morphing for each variable at all (i.e. if for some variables historical values should remain unadjusted).

Alternatively to morphing the weather file, past and future simulated weather could be constructed from a GCM simulation directly with station data only used for hourly information and variables not present in the GCMs.

A simplified method to predict future solar radiation has been used in this study. It is assumed that the distribution between diffuse and direct solar radiation is unchanged. The diffuse solar radiation is affected by cloud cover. In this initial study, the solar radiation and cloud cover are computed independently and the results are not consistent with each other. Since solar radiation has a considerable effect on the energy performance of buildings, these parameters need further work.

In this study, the impact of climate change on a MURB located on UBC campus is analyzed. The building energy simulation is conducted using the software EnergyPlus. The simulation results show that the cooling load can be expected to increase with time, and the heating load to decrease with time. Moreover, the demand for cooling is expected to increase during cooling season. With a warmer climate, there is an increased risk for overheating in buildings. Thermal comfort and risk analysis are not in the scope of this project. To enhance the understanding of overheating risk in the future, further simulations could focus on analysing thermal comfort on zone level under high temperature events. Understanding of overheating during near-extreme weather events is of specific importance.

Further analysis is recommended to understand the impact of climate change on thermal and energy performance of archetypes with different design options such as size and orientation, as well as building design features including window-to-wall ratio, glazing, shadings, thermal insulation, natural ventilation

strategies etc. There is a growing interest in energy-efficient building design with strong envelopes, such as passive-houses and net zero buildings. It is important to understand how these envelopes will perform under a changing climate and if today's targets will be met also in the future.

Buildings that are built today, as well as existing buildings, will experience future climate conditions. The results from this study indicate that analyzing future performance of buildings can be expected to become increasingly important. It is crucial that we consider future vulnerability and understand future design options as well as retrofit pathways to achieve climate resilient buildings.

Weather files that account for climate change are important tools to evaluate future building performance. However, it is important that users are aware of the limitations and the uncertainties when conducting building performance simulations.

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Canadian Construction Materials Centre Guidelines for the Evaluation of Vacuum Insulated Panels

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Abstract:

Within the construction product sector, the evaluation of innovative products is not a new activity. Over the last 30 years, the Canadian Construction Materials Centre (CCMC) has conducted evaluations on various innovative construction products in accordance with CCMC Technical Guides. Over the last decade, increasing attention has been paid to improving the energy efficiency of buildings. Hence, there is currently a growing interest in manufacturing products using complex composite materials, innovative raw materials and nanotechnology to meet new energy regulations and user expectations. The use of vacuum insulated panels (VIPs) as an alternative to standardized thermal insulation products offers a far greater thermal insulating capacity, but also raises some challenges, particularly with respect to the installation of VIPs. This paper is an overview of the CCMC protocol to assess VIPs for compliance with the National Building Code of Canada (NBC), which considers two designated exterior wall applications: curtain walls and non-loadbearing steel stud walls.

Keywords:

Vacuum insulation panels, National Building Code of Canada, product evaluation.

1. Introduction

The Canadian Construction Materials Centre (CCMC) at the NRC Construction Research Center evaluates the compliance of innovative products (alternative solutions), for which there is no recognized product standard, with the National Building Code of Canada (NBC) [1]. CCMC opinions are used by building authorities throughout Canada as a basis for deciding whether innovative products are acceptable in relation to the building regulations in effect in their municipalities.

Highly insulating materials such as vacuum insulated panels (VIPs) (Figure 1) are innovative and must be evaluated as an alternative solution to the acceptable NBC solution—in this instance, standardized thermal insulation products.

The use of VIPs as thermal insulation is relatively avant-garde in the domain of building envelope applications. Thus, the amount of data on the field performance of VIPs in this domain is still very limited. Consequently, in addition to qualifying a VIP's material properties, its behavior within wall assemblies must be assessed to determine its suitability.

At the request of a consortium of manufacturers of VIPs, CCMC developed a Technical Guide outlining the test protocols and criteria for assessing the compliance of VIPs with the NBC.



Fig. 1 Vacuum insulated panel

2. Scope of the Technical Guide

The VIPs eligible to be evaluated according to the Technical Guide consist of a core made of a proprietary nanoporous material (such as nanoporous silica powder) that is encapsulated in a highly impermeable gas and vapour barrier. A desiccant (which absorbs moisture) and/or a getter (which absorbs gas) may be enclosed in the system to increase the longevity of the VIP.

A multilayer of polymer films (gas barrier) produced by lamination form an outer envelope for the core material (Figure 2 and 3). The polymer films are metallized (through the deposition of aluminum), or metal foils are laminated to the polymer films.

The encapsulated core is evacuated to a high vacuum and is then sealed to ensure that very low thermal conductivity is maintained over the expected service life of the VIP, thereby optimizing its thermal resistance performance. The high thermal resistance (low thermal conductivity) of VIPs has been reported in [2–4]. For a 25-mm-thick VIP, the thermal resistance can range from $5.3 \text{ m}^2 \cdot ^\circ\text{C}/\text{W}$ (R30) to $8.8 \text{ m}^2 \cdot ^\circ\text{C}/\text{W}$ (R50).

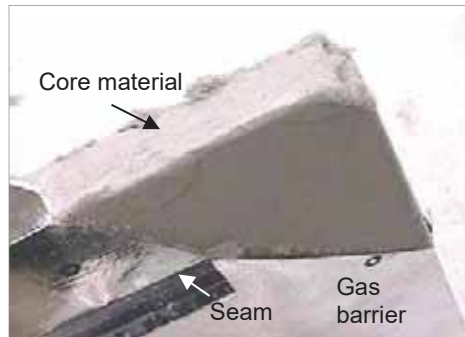


Fig. 2 VIP components [2]

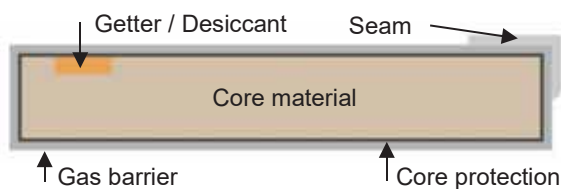


Fig. 3 Cross section of a VIP

The weakest point in the design of VIPs is the gas and vapour barrier. Therefore, the authors decided that VIPs must be mechanically protected to be eligible for qualification in accordance with the Technical Guide. This requirement lowers the risk of failure of VIPs during installation and while in service. The mechanical protection helps to prevent physical damage to VIPs that would result in a loss of vacuum and a decrease in thermal resistance performance.

The performance of VIPs can also be affected by environmental conditions, such as high temperature, high relative humidity (RH%), ultraviolet radiation, rain, and wind pressure, depending on their location within the building enclosure.

Consequently, the scope of the Technical Guide is limited to VIPs installed in the specific wall applications described in Section 4. To develop the testing protocol, a review of the factors affecting the performance of the VIP within the limits of its intended use and location within the building was conducted. The scope of Technical Guide is limited to the assessment of the thermal performance of the VIP as an element of the designated wall. The overall performance assessment (i.e., fire rating, energy performance, etc.) of the wall

assembly for compliance with the NBC is beyond the scope of the Technical Guide.

3. Qualification of VIPs as Thermal Insulation

In the first part of the Technical Guide, the basic properties of the VIP must be tested to demonstrate that its performance as thermal insulation is “as good as” the standardized thermal insulation products referenced in the NBC. To that effect, a testing protocol was developed, which is briefly summarized in Tables 1 and 2, for assessing physical and hygrothermal properties of the VIP components (barrier, barrier with seam, core) and the finished panel.

Table 1
Properties of VIP components

Component	Property
Barrier	Tensile strength
Barrier with seam	Tensile strength
Core	Density
	Thermal conductivity at different pore pressures (from 100 Pa to 5 000 Pa)
	Moisture sorption at 22°C and different RH% levels

The thermal conductivity tests on the core at different pore pressures are to be conducted in a vacuum guarded hot plate apparatus. The intent of these tests is to ensure that the VIP core under evaluation is made of nanoporous material. The thermal conductivity levels specified in the Technical Guide can only be achieved by nanoporous materials. These criteria were established on the basis of a literature review, as outlined in [4] and are not presented in this paper due to their proprietary nature.

Table 2
Properties of finished VIPs

VIP thickness	Property
All thicknesses produced	Dimensional tolerances
	Flatness
	Squareness
Maximum thickness produced	Compressive strength
All thicknesses produced	Flexural strength
25-mm-thick specimen and all other thicknesses produced	Initial thermal resistance
	Thermal resistance at failure (punctured panel)
	Change in thermal resistance following exposure to specific constant temperatures and RH% levels
	Change in thermal resistance following exposure to cycles of temperature and RH%
n/a	Estimated LTTR at 15 years

The main concern with the performance of VIPs is the reduction in their thermal resistance while in service.

In the development of the testing protocol, a study (presented in [4]) was conducted with the aim of estimating the long-term thermal resistance (LTTR) of VIPs. The study consisted of analyzing data from accelerated laboratory and field (in Canada) aging tests on VIPs of different sizes and geographical origins (Asia, Europe and North America) collected over a number of years (about 12 years) and data from accelerated laboratory aging tests on newly manufactured VIPs.

Study findings showed that exposure to moisture in combination with high temperature has an impact on the gas and vapour barrier and, consequently, on the product thermal conductivity of the VIP. Therefore, extensive exposure to variations in temperature and relative humidity is required for the evaluation of VIPs, as summarized in Table 2.

In addition, on the basis of these data, a thermal resistance aging profile was derived to provide guidance to building designers on the LTTR of VIPs. The recommended design RSI value for a 15-year service life corresponds to 70% of the initial RSI value established in accordance with Table 2. VIPs meeting the criteria associated with Table 2 are deemed to meet the design estimated LTTR.

4. Performance of VIPs in Designated Walls

Two types of exterior walls were designated for VIP applications by the consortium of manufacturers involved in the development of the Technical Guide: curtain walls (spandrel areas) and non-loadbearing steel stud walls.

4.1 Spandrel Panel in Curtain Walls

The designated protection method for this application consists of encapsulating the VIP in an insulated glass (IG) unit designed for the spandrel areas of curtain walls (IG units are fixed to mullions) (Figure 4).

The environmental conditions exerted on the IG unit were then considered to determine the potential impact on the VIP. It was assumed that the environmental conditions affecting the encapsulated VIP would be limited to ultraviolet (UV) radiation, temperature variations, and wind loads, conditional to the IG-VIP unit meeting the Technical Guide requirements (the durability of the seal being of main interest) and, the VIP meeting Tables 1 and 2. As UV radiation can be controlled by applying a UV protection film on the glass, wind loads remained the main potential issue to address.

Wind pressure causes the glass panes to bend inward and outward which, in turn, may cause the IG-VIP unit as a whole to bend. Therefore, a test protocol was

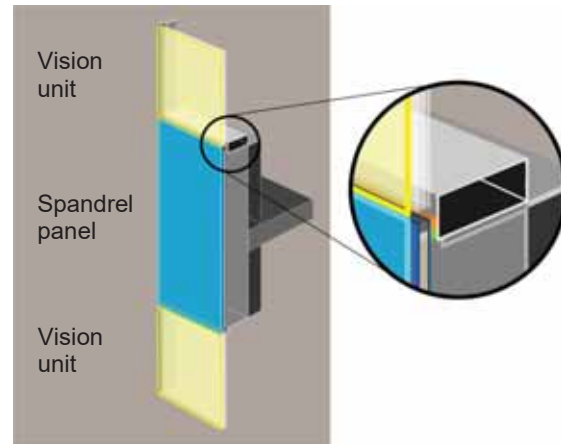


Fig. 4 Spandrel area in curtain wall

developed to assess the effect of wind on the encapsulated VIP. The intent of the test protocol is to determine whether the IG-VIP unit can maintain its thermal resistance performance at an acceptable level after being subjected to wind load cycles (sustained, cyclic and gust pressure). A minimum 2 440 mm × 2 440 mm curtain wall test assembly (stick system) with installed IG-VIP units was considered in the protocol.

The IG-VIP unit under evaluation must initially be tested to establish its thermal resistance performance and then installed in the full-scale wall assembly for exposure to the wind loading schedule. Following exposure to the wind loading schedule, the IG-VIP unit is then extracted from the wall and tested again to assess its thermal resistance change using a guarded hot box apparatus. The intent of this test is to assess whether the VIP maintains its thermal resistance performance after being exposed to wind pressure.

4.2 Non-loadbearing Steel Stud Wall

For this application, VIPs are planned to be installed on the exterior side of non-loadbearing steel stud walls and to be protected on all sides with thermal insulation board, such as expanded/extruded polystyrene (EXP/XPS) or an equivalent board. Proprietary z-girts are expected to be used to mount the VIPs onto the wall. Also, a sheathing membrane or other code compliance measures are expected to be used to ensure moisture protection.

Under these installation conditions, the impact of wind pressure on the performance of the VIPs also remains the main concern. Will deflection caused by wind loading have an impact on the thermal resistance performance of the VIP? Consequently, a test protocol (on a minimum 2 440 mm × 2 440 mm test assembly) was developed to assess the change in thermal resistance performance of the VIP after exposure to wind load cycles (sustained, cyclic and gust pressure). The pressure levels are selected according to the

building type (high- or low-rise) in which the VIP is planned to be installed.

For this application, the effective thermal resistance values of the wall before and after wind loading must be compared to assess whether the VIP can maintain its initial thermal resistance performance.

5. Conclusions and Outlook

The use of VIPs in wall applications offers designers an innovative alternative solution to standardized thermal insulation products. As reported in the literature, the higher thermal resistance performance of VIPs is expected to improve the overall effective thermal resistance of the walls and, consequently, the energy efficiency of the building. Even if the gas and vapour barrier is punctured or its properties deteriorate with age, the thermal resistance value of the VIP is expected to remain higher than that of traditional insulation.

Compliance of VIPs with the NBC can be demonstrated through the proposed testing protocol (which assesses physical and hygrothermal properties, as well as durability) when the VIPs are used within the conditions and limitations specified in the Technical Guide. This Technical Guide represents the first set of testing guidelines for assessing VIPs for compliance with the NBC.

Future investigations will focus on improving the service life assessment of VIPs by developing a test method and enhancing the service life assessment to a 25-year target.

Since VIPs cannot be cut on site to fit wall irregularities because of construction realities, a well-thought-out design, in terms of the number and size of VIPs to fit the overall wall surface, is required. Traditional insulation can also be used to compensate for small irregular areas.

Another issue affecting VIPs is the effect of thermal bridges created by the metallized films, as explored in [5]. For energy efficiency assessment, measurements of the effective thermal resistance of the wall should be considered, in addition to measurements of the thermal resistance of the VIP itself.

Finally, but of no less importance, is the issue of modifications made to walls incorporating VIPs. Measures should be taken to ensure that building owners and maintenance staff are aware of the locations of VIPs in the building enclosure so that maintenance, interior design changes, and retrofit are adequately planned to avoid puncture of the VIPs which is hidden from view.

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Acknowledgements

CFD analysis of air flow in buildings with sustainable design

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Abstract—A considerable amount of Greenhouse Gas Emission (GGE) takes place due to either heating or cooling of buildings. Retail spaces and offices along with adjoining public space, commonly a courtyard are among the most energy-intensive building typologies. Their design without proper consideration of insulation, ventilation and other variables can lead to a considerable increase in energy usage. At the same time maintaining the air quality at commercial buildings and public spaces had been a challenging endeavour for architects and designers. Current research investigates the role of Computational Fluid Dynamics (CFD) in the design of courtyards with focus on improving the building's energy performance by utilizing natural ventilation.

Index Terms—Canadian Model National Energy Code for Buildings, Computational fluid dynamics, Courtyard design, Building energy performance, Finite volume mesh.

1. Introduction

Evaluating a building's energy performance is the key first step in understanding and reducing its energy consumption and carbon footprint. The standards set for building's energy consumption in Canada are based on 1997 *Canadian Model National Energy Code for Buildings (MNECB)* [1]. The annual site energy intensity for a baseline case recommended by code is 275 kWh/m², while the annual energy consumption in Canadian office/education buildings varies from 100 to 1000 kWh/m² of conditioned floor space depending on location, construction, use and type of office equipment, operating schedules, HVAC and lighting installations. CanmetENERGY's research on end-use of load characteristics of residential and commercial air-conditioned office buildings has revealed that air-conditioning accounts for 60% of total building electricity consumption in Canada. Thus there is a need to consider passive design options (*e.g.*, building form, orientation, and envelope) more carefully and to enhance indoor air quality by energy-efficient means. The existing literature in building sciences suggest some gray areas in the implementation of traditional passive design concepts in the modern context as well as scientific validation of these concepts.

Natural ventilation has been globally used as one of the natural passive cooling strategies recommended for hot-arid regions. In some dry areas these strategy had been utilized to maintain appropriate thermal comfort for inhabitants of the building [2]. With climate change, adaptive energy efficient buildings suited for extreme weathers are the developing state-of-art in construction industry [3]. For centuries courtyards have been designed to utilize natural ventilation [4].

Besides natural ventilation, courtyards serve as reservoirs collecting cool air in night and provide shade in the equatorial and tropical sunlight [5]. Experimental studies to evaluate the effect of ventilation on the thermal performance of houses in hot-arid region found that courtyard gives high efficiency in providing cool indoor air through cross ventilation [6]. In a similar numerical work [7], the flow inside a building with courtyard was validated with experimental studies of [8].

The energy efficiency analysis of commercial and residential buildings has been primarily based on fundamental heat balance principles. These models are solved using linear techniques and thus are fast in simulating heat transfer scenarios. Linear methods (*e.g.* boundary element methods) either do not include the transient heat transfer associated with air flow in the building or suffer from assumptions simplifying it to one-dimensional effects. These constitute a major set of limitations since buildings are designed to operate over a wide range of climatic conditions, and in reality, experience short term seasonal and long term climate change. To consider the full range of effects, the physics can be described using the Navier-Stokes equations and solved using Computational Fluid Dynamics (CFD). A CFD model can capture complex flow phenomenon like buoyancy driven flows, vortex shedding, multi-scale eddy motions etc. Accurate simulation of these phenomena can vastly improve the accuracy of thermal load evaluations in energy calculation and hence reduce the emission of GHG.

The open-source preprocessing and solver software OpenFOAM[®] has facilitated the development of building engineering by providing a tool to solve air flow using Reynolds Averaged Navier-Stokes (RANS) as well as Large Eddy Simulation (LES). The libraries in OpenFOAM[®] can be modified and extended to implement user defined boundary conditions. This feature of OpenFOAM[®] was exploited to develop relevant boundary conditions accounting for realisting conditions.

The traditional concept of buildings with courtyard has been analyzed in this paper from perspective of energy efficient building design using CFD simulations. The results have been validated with the published results of [7].

2. Numerical model

This section has been divided into several parts which briefly touch upon the governing equations of fluid flow and various discretization schemes used.

A. Governing equations

The Reynolds Averaged Navier-Stokes (RANS) equations are time-averaged equations of motion for fluid flow. These equations are derived by time averaging of the Navier-Stokes equations. For an unsteady, incompressible, turbulent flow the continuity equation (Equation 1) and the momentum equations (Equation 2) are:

$$\frac{\partial U_i}{\partial x_i} = 0 \quad (1)$$

$$\rho \frac{\partial U_i}{\partial t} + \rho \frac{\partial U_i U_j}{\partial x_j} = \rho g_i - \frac{\partial p}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j} + \mu \frac{\partial^2 U_i}{\partial x_j^2} \quad (2)$$

where ρ is fluid density, x_i ($i = 1, 2, 3$) represent x, y and z directions respectively, t is time, g_i ($i = 1, 2, 3$) are the body force intensities in x, y and z directions respectively, p is pressure, U_i ($i = 1, 2, 3$) is the resultant velocity components in x, y and z directions respectively, U_j ($j = 1, 2, 3$) are the mean velocity components in x, y and z directions respectively and μ is dynamic viscosity of the fluid. In the above $\tau_{ij} = -\rho \overline{u'_i u'_j}$ represents the Reynolds stress components and u'_i ($i = 1, 2, 3$) are the components of fluctuating velocity in x, y and z directions respectively. These equations cannot be solved directly as they no longer constitute a closed set and require additional equations in the form of turbulence models. The aim of any turbulence model is to express the Reynolds stress in terms of known or calculable quantities. In Cartesian coordinates the components of the viscous stress tensor which represents additional momentum transfer due to turbulent fluctuations are defined based on the Boussinesq eddy viscosity hypothesis as:

$$\tau_{ij} = -\frac{2}{3} \rho k \delta_{ij} + \mu_t S_{ij} \quad (3)$$

$$S_{ij} = \frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i} \quad (4)$$

In the above δ_{ij} is Kronecker delta ($= 1$ when $i = j$, otherwise 0), k is the kinetic energy, μ_t is the turbulent viscosity and S_{ij} is the mean strain rate.

As the Reynolds stresses are not known, appropriate turbulence models (realizable k - ε in current study) are introduced for calculating these stresses and their interaction with the mean flow variables. These models are called closure models. The additional viscosity due to turbulence of flow known as the turbulent viscosity μ_t is given by Equation 5 as below:

$$\mu_t = \rho C_\mu \frac{k^2}{\varepsilon} \quad (5)$$

where C_μ is calculated from Eq. 6 for realizable k - ε model.

$$C_\mu = \frac{1}{A_0 + A_s k U^* / \varepsilon} \quad (6)$$

A_0 is a model constant ($= 4.0$), where as the parameter A_s is a function. Readers are directed to [9] for further curiosity on model parameters used in realizable k - ε turbulence models.

B. Turbulence modelling

In this study the realizable k - ε model [9] for turbulence has been used. This turbulence model belongs to the family of 2-equation eddy viscosity models and involves two transport equations, one for the kinetic energy (k) and other for the dissipation rate of the kinetic energy (ε). The transport equations for k and ε are:

$$\rho \frac{\partial k}{\partial t} + \rho \frac{\partial (k U_j)}{\partial x_j} = -\rho \overline{u'_i u'_j} \frac{\partial U_i}{\partial x_j} - \rho \varepsilon + \frac{\partial}{\partial x_j} \left[\left(\frac{\mu_t}{\sigma_k} + \mu \right) \frac{\partial k}{\partial x_j} \right] \quad (7)$$

$$\rho \frac{\partial \varepsilon}{\partial t} + \rho \frac{\partial (\varepsilon U_j)}{\partial x_j} = C_{\varepsilon 1} \frac{\varepsilon}{k} \overline{\rho u'_i u'_j} \frac{\partial U_i}{\partial x_j} - C_{\varepsilon 2} \rho \frac{\varepsilon^2}{k} + \frac{\partial}{\partial x_j} \left[\left(\frac{\mu_t}{\sigma_\varepsilon} + \mu \right) \frac{\partial \varepsilon}{\partial x_j} \right] \quad (8)$$

where $C_{\varepsilon 1}, C_{\varepsilon 2}$, are constants, σ_k and σ_ε are the turbulent Prandtl numbers for k and ε respectively. The values of the constants for realizable k - ε turbulence model are as follows: $C_{\varepsilon 1} = 1.44$, $C_{\varepsilon 2} = 1.9$, $\sigma_k = 1$, $\sigma_\varepsilon = 1.2$.

C. Discretization schemes

The governing equations are solved at the center of the cells in a finite volume domain discretized into structured hexahedral cells. The discretisation scheme used for the Laplacian and gradient terms as $\nabla \cdot (\mu \nabla U)$ is Gauss, and the interpolation scheme for the diffusion coefficient (μ) is linear (central differencing) with explicit surface normal gradient scheme which includes non-orthogonal correction. For the divergence terms the discretisation scheme used is Gauss and the interpolation schemes for velocity (U), turbulent kinetic energy (k) and dissipation of kinetic energy (ε) is first/second order, bounded. A first order, bounded implicit scheme is used for the first time derivative. The algorithm used for the resolution of the governing Equations 1 and 2 is based on the PIMPLE method which is a combination of the algorithms SIMPLE (Semi-Implicit Method for Pressure Linked Equations) and PISO (Pressure Implicit with Splitting of Operator). The SIMPLE algorithm [10], [11] is used to solve steady-state problems with emphasis on the treatment of the non-linear effects of the velocity rather than the precise determination of the pressure field. Each iteration is assumed to be a pseudo time step. Stability is assured and convergence is improved by under-relaxation of fluid properties. The PISO algorithm [12], is suitable for solving the velocity-pressure coupling for each time step in a transient simulations.

3. Case Description

To numerically simulate fluid flow phenomenon, the setup primarily involves a domain which can be discretized into small volumes known as cells. Each cell has faces and a cell centre. In a segregated solver, the pressures are calculated at the cell centres while the velocity is calculated at the face centres. The faces at the extent of the domain are known as boundary patches and boundary conditions are set on these patches. In current study, the computational domain consists of a Numerical Wind Tunnel (NWT) and a model (rooms

and courtyard). The NWT acts as an infinite domain for providing surrounding condition to the entrance of courtyard. The model is at the bottom boundary of the wind tunnel. The simulations were performed on a full scale model. The domain and the model are as shown in Figure. 1. A detailed description of the numerical wind tunnel and the model setup is presented below.

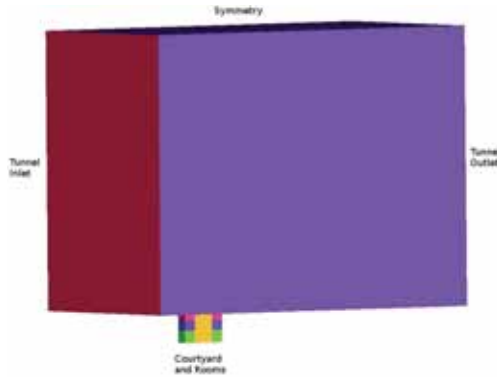


Fig. 1. View of the numerical wind tunnel and the model

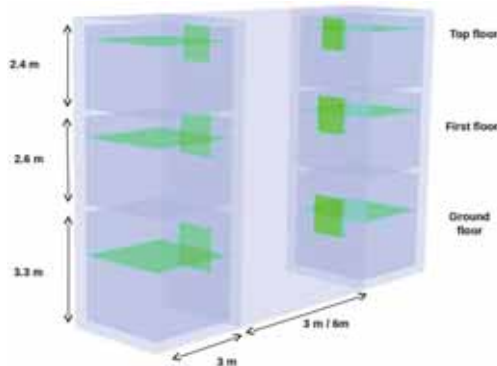


Fig. 2. Dimensions of the rooms and courtyard. Position of horizontal planes to obtain measurements of velocity at the height of 2 m. Vertical planes are entry to each room and are used for measurement of mass flow rate and velocity distribution

A. Numerical wind tunnel

The Numerical Wind Tunnel is a 3D replica of a surroundings that influences the flow in the courtyard. In the current study the height of the rectangular tunnel $H = 9h$, where h is the depth of the courtyard. The length of the rectangular tunnel $L = 1.2H$, while the width of the tunnel $W = 0.8H$. The location of the line passing through the centre of courtyard is set at a distance of $0.3H$ from the inlet to the tunnel. The inlet is located at the left most end of the tunnel, while the tunnel outlet is located at $0.7H$ from the axis passing through courtyard centre. The top of the tank is situated sufficiently away from the courtyard to have negligible influence on the flow in the courtyard.

B. Model

The rooms and courtyard are collectively referred as model, and constitute that section of the setup were anal-

ysis of the air flow is done. Two different scenarios were studied. In these scenarios only the width of the courtyard was different and all other parameters were kept identical. In these scenarios the width of courtyard were 3 m and 6 m, respectively. The depth for courtyard for both cases is 9 m. Thus the two cases have a w/h ratio of 0.33 and 0.66, respectively. Hereafter, these cases will be referred as 'Narrow courtyard' and 'Wide courtyard'. These dimensions are common in hot-aided regions, and can be scaled to include any commercial space. Three floors of rooms, on either side of the courtyard were analysed. Since the retail spaces require higher ceiling height compared to office space the vertical dimensions have been considered to vary from 3.3 m at ground floor to 2.6 m for middle floor and 2.4 m at top floor. The window dimensions on both sides of the courtyard for each floor have been proportional to the room sizes. Thus the window dimensions for ground, middle and top floor had been $1.4 \times 1.4 \text{ m}^2$, $1.3 \times 1.3 \text{ m}^2$ and $1.1 \times 1.1 \text{ m}^2$, respectively. The floor area for all the levels has been kept to $3 \times 3 \text{ m}^2$. The dimensions of the components of model are shown in Figure 2.

C. CFD domain

The grid for the numerical wind tunnel and the model has been generated using proprietary preprocessing software Ansys ICEM-CFD. The distribution of cells in the entire domain and close to the model is shown in Figure 3, respectively. The numerical domain has been discretized into 55000 hexahedral cells. The distribution of cells is non-uniform with finer cells close to the model. This is the region of interest and high flow gradients are expected in these regions as the air from upstream enters the courtyard and the rooms. The mesh in the model is uniformly distributed with high resolution, as it is the region we are particularly interested in.

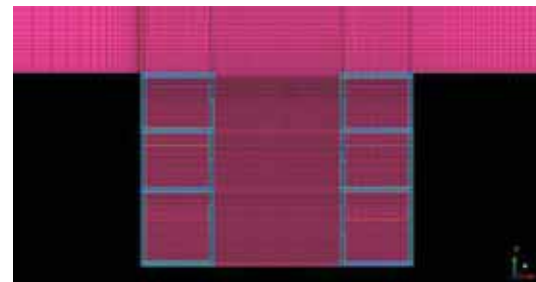


Fig. 3. Cut section visualization of the structure of mesh in the domain

4. Boundary conditions and Model settings

The boundary conditions were implemented on those faces of cells which are on the boundary. In current case, boundary conditions were prescribed on tunnel inlet, tunnel floor, tunnel outlet and wall of the model. The parameters used to prescribe the boundary conditions were velocity U , pressure p , kinetic energy k , dissipation of kinetic energy ε and their gradients. At the tunnel top, normal gradient of velocity prescribed was 0, while k and ε were prescribed based on the direction of U i.e. when the velocity vector points out of the domain the boundary condition is a Neumann

boundary condition otherwise it is a Dirichlet boundary condition. At tunnel outlet static pressure was assumed to be 0 Pa and the value of turbulence parameters were same as that at the tunnel top. At the tunnel inlet, velocity and turbulence parameters were prescribed as a profile, through a user defined code. The reference velocity was set to 8 m/s which is the normal ambient velocity during most part of the year. A power law of 0.18 was used for velocity boundary condition at inlet. This treatment provides realistic condition for boundary layer formation close to the building height. The value of velocity increases as we move away from the building towards tunnel top.

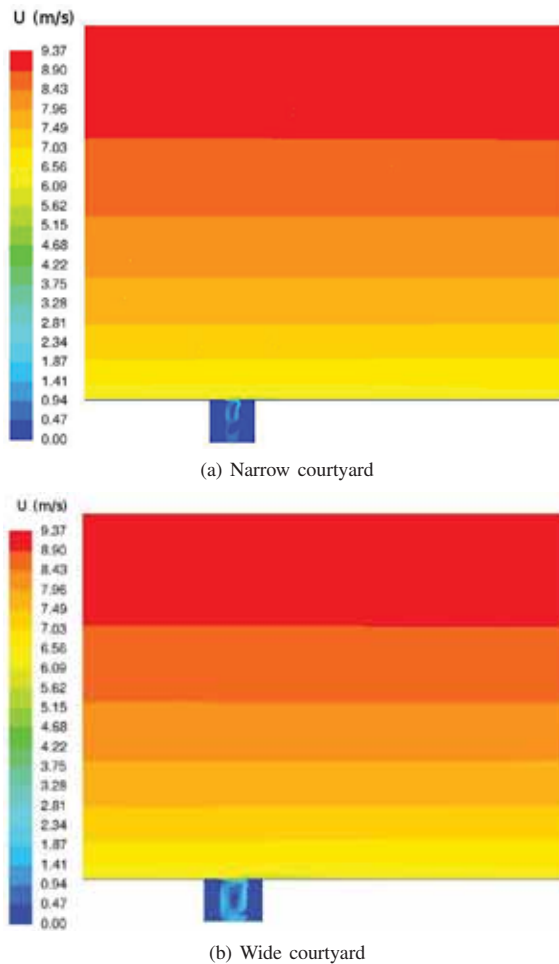


Fig. 4. Velocity contours at the mid section of the domain

At the tunnel walls, bottom and model walls; normal gradient of pressure was set to 0 i.e. $\hat{n} \cdot \nabla p = 0$. The velocity specified on the tunnel walls, bottom and model walls was 0. The values of k and ε on all the walls were based on standard wall function specifications. Minimum value of y^+ was found to be ≈ 2 and ≈ 3 on model walls respectively for most of the simulation.

5. Results and discussions

The distribution of velocity along the mid section of the tunnel and model is shown in Figure 4. The implementation of

the user defined velocity profile can be seen from the velocity contour in the domain. Air velocity in the domain increases as we move towards the tunnel top.

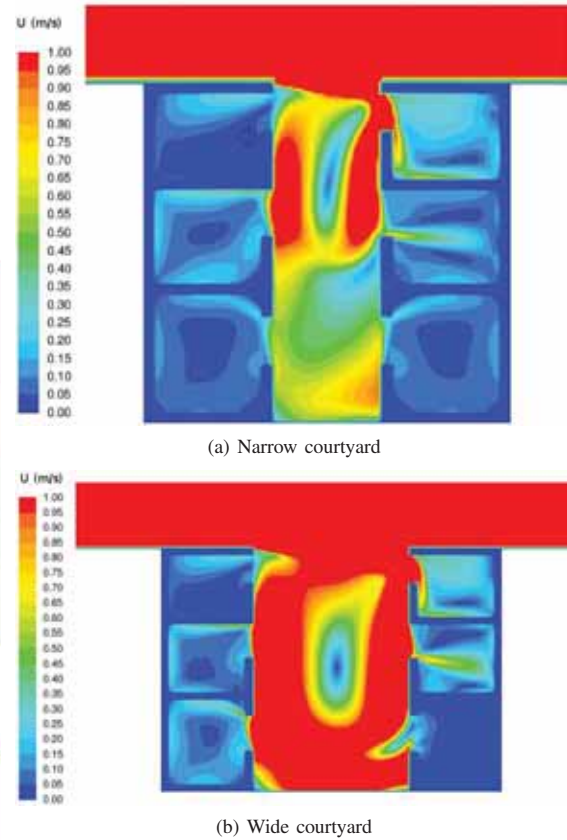


Fig. 5. Velocity contours at the mid section of courtyard and rooms

The velocity distribution at mid plane close to the model has been shown in Figure 5. It can be concluded that the magnitude of velocity for most of the courtyard is higher for wide courtyard compared to narrow courtyard along with uniform distribution on the walls separating the rooms from the courtyard for all the floors. The overall distribution of velocity inside the rooms on both sides of courtyard and for all the floors is uniform for the case of narrow courtyard compared to wide courtyard. It can be seen that the air flow is minimal in the room on right side of ground floor. Thus the dissipation of thermal energy from this room is minimal, and hence an appropriate usage of this space would bring down the energy requirement of the building. These types of contours can be very helpful for architects and interior designers to design an energy efficient building. The pathlines of air particles inside the model have been shown in Figure 6. Pathlines are trajectories that individual fluid particles follow. The patterns of pathline suggest, that in narrow courtyard flow reaches left room of ground floor and right room in the middle floor before reaching any other room. Similarly in the wide courtyard right room in top floor receives air before any other room. The three dimensional movement of air particles can also be seen from Figure 6, these complements over the two dimensional studies of [7].

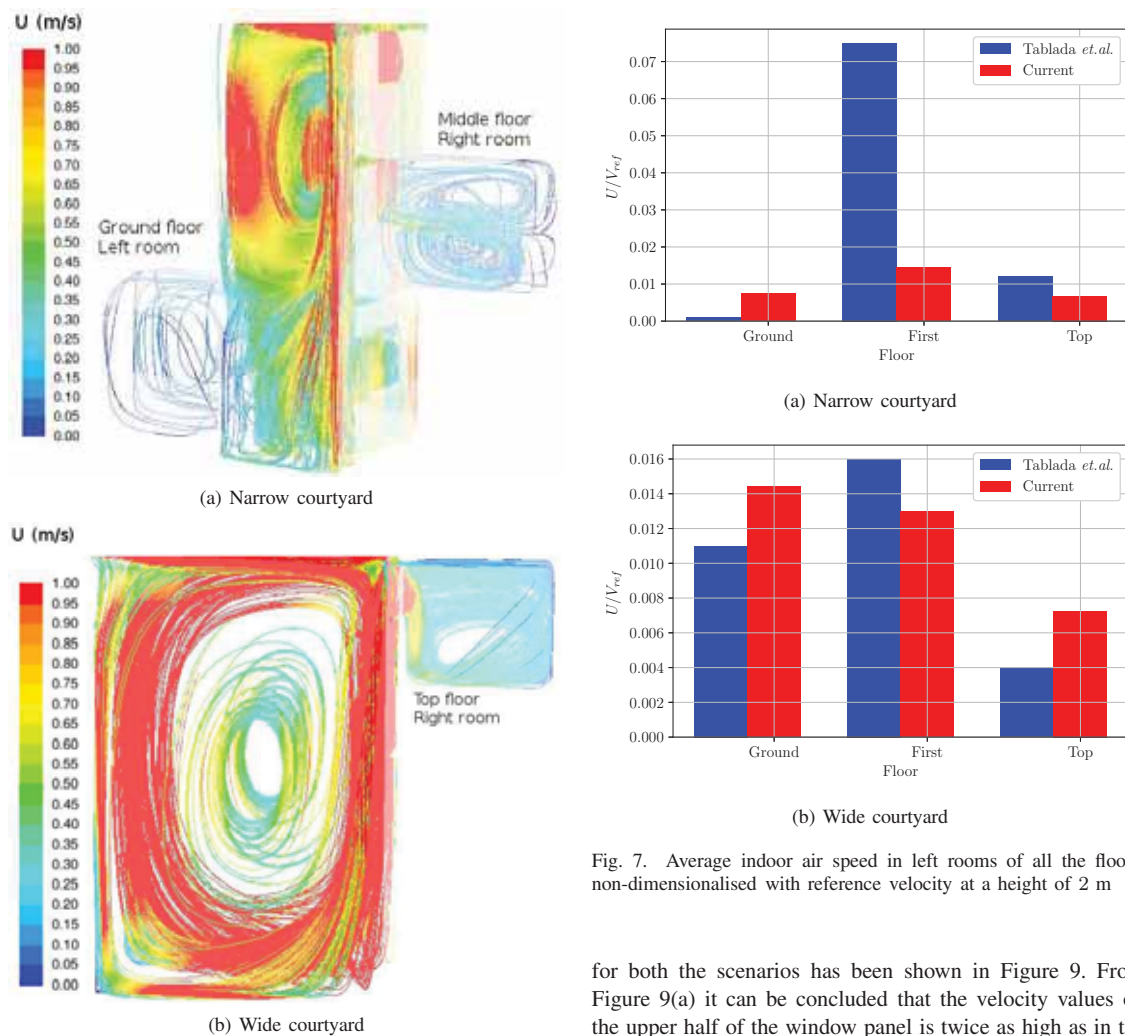


Fig. 6. Velocity contours at the mid section of courtyard and rooms

Considering the possible location of the occupants inside the room, the average indoor air speed has been measured at a height of 2 m inside each room, and have been shown in Figures 7 and 8 for the two scenarios discussed earlier. Comparison has been made with published results of [7], and it has been found that air speed in these studies differ significantly. The previous study was a two dimensional study and it is expected that simulating the third component of velocity would represent a realistic flow field. Pressure difference inside the room and in the courtyard differ significantly at different levels; also circulation pattern along with the fact that the rooms at different levels have different opening sizes contribute to the velocity in the third direction.

The average indoor air speed when the windows are open and distribution of velocity over the windows and exterior walls when windows are closed, is an important parameter in building design. These data will help in understanding the thermal dissipation, choice of insulation and thereby controlling the thermal losses. The distribution of air velocity on the windows of each floor for the left and right rooms

Fig. 7. Average indoor air speed in left rooms of all the floors, non-dimensionalised with reference velocity at a height of 2 m

for both the scenarios has been shown in Figure 9. From Figure 9(a) it can be concluded that the velocity values on the upper half of the window panel is twice as high as in the lower half. Whereas it can be seen from Figure 9(b) that the distribution is uniform on windows of the rooms located on right side of the courtyard.

Indoor air quality is an important parameter for calculation of comfort in a commercial or residential building. Circulation of air is an important parameter in improving the air quality. Even though artificial ventilation plays an important role in maintaining the air quality, it is often associated to increase in the GHG emission as well as increase in building's energy requirements. Natural ventilation of air can contribute significantly in reducing the energy requirement of a building. Coupling natural ventilation with a building's HVAC system via a feedback control system could improve the air quality as well as improve the energy performance of the building.

The amount of air entering the courtyard and individual rooms can be calculated by measuring the mass flow rate across the windows in open condition. The amount of air flowing into the rooms have been plotted as % of total flow rate into the courtyard in Figure 10. It can be seen that the amount of air entering the right room on top floor is significantly higher for both the narrow and wide courtyard. The flow rate along the height of courtyard is uniform across

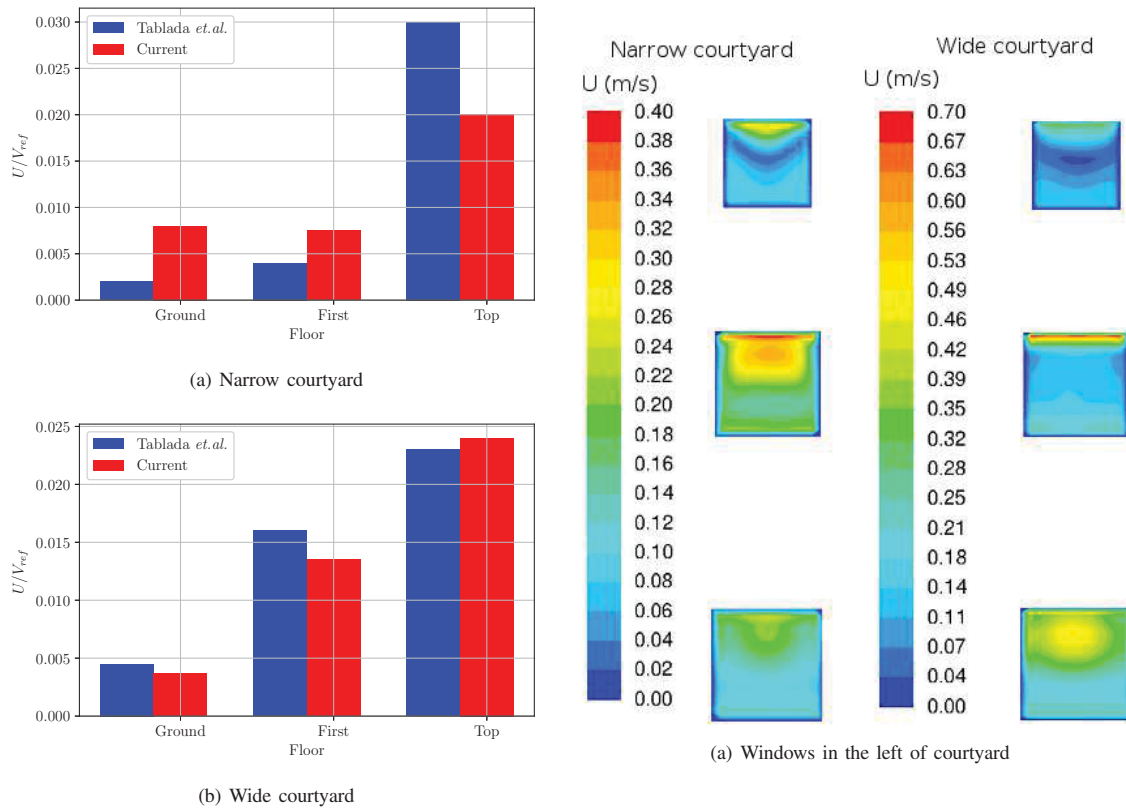


Fig. 8. Average indoor air speed in right rooms of all the floors, non-dimensionalised with reference velocity at a height of 2 m

the windows in the left side, but varies significantly across the windows on the right side of courtyard.

6. Conclusions and outlook

A high fidelity numerical method was presented in this paper to demonstrate the application of CFD in design of energy efficient buildings. Two designs of courtyard were analysed and compared. These designs differed in the measurements of floor areas of the courtyard. The parameters like indoor air speed, indoor air quality, flow pattern, wind velocity distribution etc. were studied. The numerical results were compared with the results of published two dimensional CFD analysis. Previous study used a two dimensional flow field for measuring the average indoor air speed at a plane, it was expected and found that extending the study in third dimension would improve the accuracy of these values.

The distribution of air inside the courtyard and in the adjoining rooms can help in understanding the distribution of thermal energy. It was found that increasing the w/h ratio of courtyard significantly increases the circulation and hence the air quality in the public space, whereas narrow courtyard under the windows open condition facilitates proper ventilation inside the rooms. Average air speed inside the rooms of building with wide courtyard and narrow courtyard were compared. It was found that the average air speed in the rooms on either side of narrow courtyard was uniform for

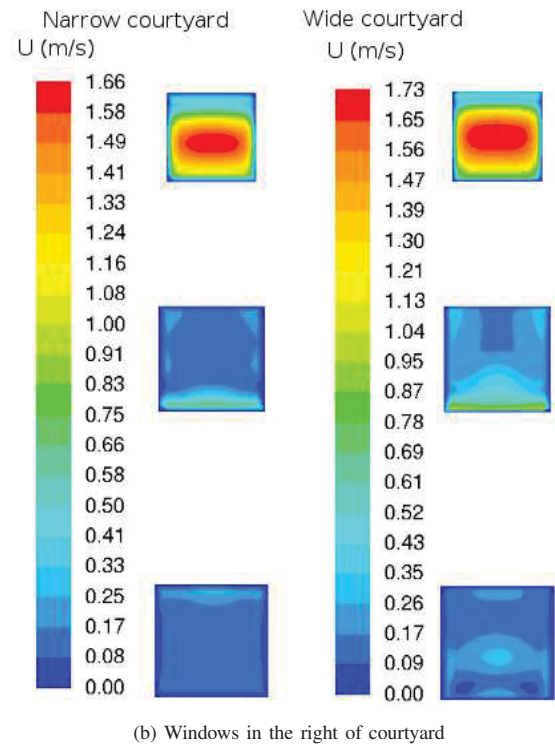


Fig. 9. Velocity distribution on the windows at all the levels on either side of the courtyard

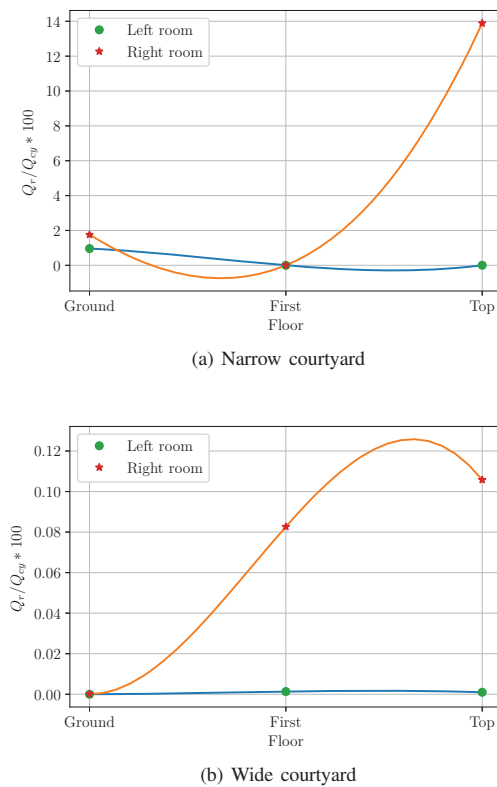


Fig. 10. Flow rate at the windows as a percentage of flow entering the courtyard

all floors except the room on top floor on right side. Where as in the building with wide courtyard the air speed increases as we go to upper floors in right side rooms but decreases inside the rooms on the left side. The maximum air speed can be found on the windows of upper floor. The maximum mass flow rate of the air can be found across the windows on the right side of the the courtyard for both the w/h ratio and increases from ground floor to the upper floor. Current research iterates that CFD can be an effective tool for the architects and civil engineers, for designing energy efficient buildings.

Acknowledgement

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SUSTAINABLE- ECO- BUILDINGS ASSESSMENT METHOD FOR THE EVALUATION OF RESIDENTIAL BUILDINGS IN HOT DRY CLIMATE

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Abstract:

This research aims to investing the present situation of residential buildings in Greater Khartoum to evaluate them by sustainable environmental parameters. The problems of residential in the indoor and outdoor environment and services. The research also aims to find a sustainable assessment method to enable us to evaluate residential areas and their services in the Greater Khartoum.

The methodology of the research starting by literature review. Identify the passive and sustainable solutions suitable to hot dry climate. This method contains eight main categories which are, sustainable site, indoor environmental quality, outdoor thermal control, building form, materials and resources, water supply, power supply system and environmental plan process. The total points achieved should be 125 points, the method has a scale of points for evaluations, main categories and sub issues calculate the total of points to get the result of evaluation for the building. The scale, of evaluation and range of evaluation from pass, good, very good and excellent according to the study method of assessment.

The survey starts by identifying the standards of selecting the case study, tools of investigation, and the documentations methods, interviews with professionals and owners; then survey studied forty-eight cases in the residential areas in Greater Khartoum, analyzing the data by the evaluation method of the research, summarizing in tables and figures.

The finding by the method of assessment and got the result as; zero of the case studies were Excellent, 18.75% of the cases studies were Good, 25% of the cases studies were PASS and 56% were Weak. The analysis of buildings showed Good results in sustainable site and outdoor thermal control and indoor environmental control. Weak result in building form, materials and resources and services, such as drainage system, water supply system, power supply system and environmental process in the first class areas and shows Weak results in all categories in the areas third class areas General conclusions for areas of study in the main categories are set in the conclusion. Conclusion and Recommendations in urban, housing, services, building construction and community level are set up to be applied in sustainable ecological building in Greater Khartoum

Keywords:

Passive solutions, Sustainable Eco Building Principles, Sustainable Assessment Methods, Greater Khartoum Environmental parameters, Introduce Assessment method for evaluation of residential buildings.

1. Introduction

This research aims at investigating the present situation of residential buildings in Greater Khartoum to evaluate those buildings using sustainable environmental parameters. The problems of residential buildings to that will be investigated are environmental problems in the indoor and outdoor environment and services. The research also aims to find a sustainable assessment method to enable us to evaluate residential areas and their services in the Greater Khartoum. The location of the case study is in The Greater Khartoum, which is classified into the three towns, the capital Khartoum, Khartoum North and Omdurman. The climate described as hot dry climate, it between latitude 15° 36' north and longitude 32° 3 east, with an altitude of 380 meters above sea level, The temperature in summer ranges between 40°C to 45°C, in winter it drops to 14°C to 25°C. The rains range between 100mm to 150 mm. The range of relative humidity is 40% to 60%. Greater Khartoum is facing floods, desertification and rare

earthquakes and it has wide variety of natural vegetation's in the lands around River Nile.

2. The Literature Review

2.1 The Passive solutions and Environmental Principles suitable to hot dry climate

The aim of this paper is to define the sustainable-eco-building principles in relation to the environment, and at the end, we will study all suitable solutions to hot dry climate to be applied in sustainable-eco-building and environmental comfort. Sustainable development started in 1992, Sustainable development define as: that meet the needs of the present without compromising the ability of future generations to meet their own needs this concept has been explained by Conway, 1987.

The building design should be economical in: reducing costs of materials, building construction, maintenance, building equipment's, energy and water consumption and there is a need to focus on the fact that the building should be socially connected to the surrounding environment, by providing social services, recognizing human health and safety and to improve

the quality of life; beside that the building should be controlled in, British Architects' (Architect, 2010) considered minimum issues key indicators for sustainability design and grouped them according to the structure issues to be recommended for consideration which are: Land and ecology, Community, Health, Materials, Energy and water. (Kubba, 2010) Today new concepts of architectural design allow us to greatly improve the energy performance and to reduce the environmental impact of materials use in buildings. The Leader in Energy and Environment (LEED) announced six main categories of sustainable design, which are Sustainable Site, Indoor environmental quality, the energy, the water, the material and innovation.; As well as there are many books discussing the issues of sustainable design and eco design principles one of these books is: (Kubba, 2010) and (Fower, 2006) discussed these issues in his book 'LEED Practices, Certification, and Accreditation Handbook as well as (Bromberek, 2009) discussed the principles of designing eco resorts which are site selection and landscape, construction, energy management, water management, waste management, climatic performance in addition to that (Barrows, 2009) .(Sassi, 2006) And (Van, 2009) published a book in 1996; they discussed the principles of ecological design which are: Solutions Grow from Place, Ecological Accounting Informs Design, Design with Nature; everyone is a Designer, Make Nature Visible. The book's second part, title is "The Ecological Design Process Sustainable site, Energy, water, materials; economic dimension which will appear in such solutions as energy efficiency, water efficiency and ecological building material, recycling of grey water, recycling of construction materials. The social dimension, this appears in community participation, and managing the outdoor environment. Then; provides an introduction to each principle, and provides sustainable and technical solutions for each principle from global position that has been applied. (Roaf, 2005). reviews the literature on thermal comfort principles and design with reference to the hot-dry climate. discuss the basic thermal comfort principles; thermal comfort definition, the heat balance between human and the building, the heat flow, the time lag, human thermal comfort and balance, building thermal behavior, the building material and the important of ceiling and wall insulation in such climate as hot- dry climate and the six basic factors of thermal comfort. the passive solution in architectural design suitable to hot dry climate such as urban planning control and spatial control, architectural element and components control, physical aspect control and controlling the design in indoor environment and outdoor environment and detailing the three building components and discusses the solutions the hindrances the risks of solar radiation and high air temperature. The landscaping, and implantation of the traditional solutions such as passive cooling tower, courtyard system and controlling building form, ventilation and orientation. (Hassan, 1995) .

Why we need to introduce new assessment method for assessment the eco building in Greater Khartoum?

The global assessment method were designed for specific environment, culture, social and economic problems on those community, that's why the research highlight the need of studying the environmental, social, culture and economical needs for Greater Khartoum.

What are the suitable principles could be added to the hot-dry-climate?

(Abdelmoneim, H., 2016) discussed the global sustainable assessment methods and concluded five categories between them: sustainable site, indoor environmental quality, water efficiency, energy efficiency and material. In addition, the paper arrived to adding more categories suitable to Greater Khartoum like outdoor environment category; people in Greater Khartoum use the outdoor for sitting, collaborating, and sometime sleeping because of hot climate. Also, Building form category: studying building form is become crucial, it should be studied with solar angle to have more building shades, and better ventilation, the building should oriented towards north-south direction. In addition to that environmental design process to control the whole process in building design, construction and maintenance.

The suitability of research method of assessment and proved summary to research method of assessment that will be discussed in details.

3. Methodology

The methodology of this research the intensive study of the available assessment methods leads to the rationalization new evaluation method for testing the case study according to their nature, residential buildings in Greater Khartoum. This method has been applied to the all levels of urban classes. The Methodology consists of many steps these include:

1. Review of previous literature in Environmental Sustainable Development (ESD) and the principles of ecological design, a review of the passive solutions suitable to the hot dry climate, the nature of the case study in the environment. architectural, spatial and infra structure is reviewed as well as review the historical background of residential areas in Greater Khartoum and the problems faced by them. General review of the environmental assessment methods; the physical assessment methods and the quantitative and qualitative assessment methods and the sustainable assessment methods which had been adopted in 1992; rationalization of the new assessment method of the research to evaluate the residential buildings in Greater Khartoum. Presenting the study method of assessment and reflect the passive solutions suitable to hot dry climate into the principles of sustainable eco buildings.
2. Comparison between four sustainable buildings assessment methods was done during the research and the result was published (Abdelmoneim, H., 2016).
3. From the comparison, the researcher highlight the main principles of sustainability which are: sustainable site, indoor environmental quality, material and resources, energy and water efficiency.
 - a. Why we need to add a new sustainable assessment method that is suitable to Greater Khartoum?

The global sustainable building assessment methods were introduced in specific countries to solve the local environmental, cultural, economic and social problems. For instance, Australia introduced management, transportation and land ecology, ESTIDAMA liveable community and integrated design process, and GSAS social and culture. It was evident that all these countries had their own sustainable evaluation methods and had similar as well as different categories for solving their local social, economic, and environmental problems.

e. The need to add more categories to solve the local environmental, social, and economic problems

The researcher further added three more categories, which are as follows:

- i) Outdoor Environmental Quality: This was integrated for social and environmental impact because people use the outdoor environment for sitting, welcoming their guests, celebrating, and sometimes sleeping in hot summers. In addition, the researcher added solutions, such as the use of canopies, terraces, areas with shade, plants and trees, fountains, and the like to cool the air surrounding the buildings.
 - ii) The Building Form: This was included for economic and environmental impact. Studding the building form with solar angle provides more shade to the building and cools the air around the building; and for energy efficiency, studding the windows, vertical and horizontal sunscreens, wind towers, and courtyard system was seen to be more effective.
 - iii) Environmental design process, it was added for two reasons, to control the whole design process including the eight categories, and for educational reason, to educate the architects and engineers and the community about sustainability.
4. Present the study method of assessment in main categories, the sub issues, and the scale of evaluation, and then, criteria for selecting the case studies, the fieldwork tools, documentation, analyses, interviews with owners and specialists are also included.
 5. The fieldwork including a survey to evaluate 48 case studies in different areas in Greater Khartoum will be done, data collecting documenting, presenting and demonstrating them in tables and figures and analysis by computer programmes.
 6. The discussion and analyses by the study method of assessment for all areas of the study, and then the average results for the main categories of the case

studies will be done, analyzed and discussed for all areas of study in Khartoum, Khartoum North and Omdurman, then conclusion for the discussion.

7. General conclusion and recommendations will be applied in residential buildings in greater Khartoum, and recommendations for the areas of study and recommendation for the future researches will be given.

3.1 The Study of Method of Assessment

The study has reviewed environmental assessment methods including the sustainable assessment methods identifying five main principles of the study method of assessment. The literature reviewed previously; discussed passive solutions suitable to hot dry climate, also identified building form and outdoor environment and environmental design process, as well as detailed the main principles of sustainable-eco-buildings. To conclude the main categories of the study method of assessment are: sustainable site, indoor environmental quality, outdoor environment, water efficiency, energy efficiency, building materials and building form and environmental design process. The study method of assessment shall be explained and detailed.

3.2 Development of the study method of assessment

The research method of assessment has been developed using different methods:

1. By carrying out intensive literature review in the area of the study, including the principles of sustainable development, principles of environmental design in urban components, architectural components, spatial aspects, physical aspects, outdoor and indoor environments, as well as studying previous assessment methods and critically analysing them.
2. Five global assessment methods of sustainable buildings are analysed; identifying the main categories for the sustainable assessment method; such as: sustainable site, indoor environmental quality, materials, energy efficiency and water efficiency.
3. After studying the environmental conditions in Greater Khartoum, the research identified three categories that are suitable for the hot-dry climate. These are: building forms, outdoor environmental quality and environmental design process.
4. Some sub issues were developed to support the research method of assessment in the field of sustainable buildings (see Appendix-6) to support the method. These issue i.e. the importance of materials in roof, walls, floors, and décor shown in the evaluation method; and the use of air conditioning as a negative (-1 point) because it has negative impact on environment.
5. Some solutions were included when reviewing literature on traditional solutions such as the use of courtyard systems, wind towers, domes and vaults effects on absorbing solar radiation.
6. Other solutions were also included based on practical experiences; such as the use of vertical and horizontal sunscreens, orientating the building at 45°, and the use of wells and septic tanks in drainage systems.

7. Technological solutions, globally and regionally, are introduced, this is by using energy simulations program to achieve energy efficiency, and using IBM software to develop eco building designs in computers.

8. Local natural resources in wind energy, solar energy, eco building materials were studied and imposed in the research method of assessment.

3.3 Scale of Evaluation

This Scale shall be used to evaluate each issue of evaluation of residential buildings in Greater Khartoum.

Table (5.1): The Scale of evaluation

The Mandatory	Meaning	Points given for evaluation
Positive	Means it's applicable	From 1 to 2
	Positive impact on the environment	1
	More Positive impact on the environment	2
negative	Means it's not applicable	0
	Negative impact to the environment	-1
	Too negative impact to the environment	-2

These points are incorporated according to The Predicted Mean Vote (PMV) and scales index.

3.4 Method of evaluation

The Suggested sustainable-eco-building evaluation method for hot dry climates, such as Greater Khartoum, which is applied in this research on the level of Eco Buildings on 48 case studies on Greater Khartoum are shown in Appendix 1.

The research has designed this sustainable-eco-building evaluation method, which is suitable to the local environment in Greater Khartoum. This contains eight main categories: Building form, materials and resources, drainage system and resources, water supply and drainage system, power supply system, environmental plan process, the total points that should be scored is 125points. What makes the difference between this method and the other three systems? The answer is: This method included other three main categories, which are outdoor thermal control, building form, and environmental process as a separate category. Also, this method gives five main evaluation ranges of points which are:

< 40	Weak
(40 - 44 pts)	Pass
(45 – 59),	Good
(60 - 75 pts)	Very good
(76-126pts and more)	Excellent

These levels of evaluation were included in reference to British standards of green buildings BREEAM. (BREEAM, 2014) That uses the same method of evolution: weak, pass, good, very good, excellent.

The method of assessment that has been applied to the 48 samples in different areas in Greater Khartoum., the sustainable-eco-buildings assessment method was designed after wide review of the environmental assessment methods and the suitable passive solutions

for hot dry climate. The method combines sustainable main categories, and the passive solutions. Taking into account the environmental, spatial, architectural, residential and technological conditions of the case studies.

3.5 The Main Categories of the Method of Assessment

Table 5.2: main categories of the assessment method

item	category	symbol	No. of points
1	Sustainable Site	SS	13 points
2	indoor environmental control	IEQ	34 points
3	outdoor thermal control	OTHC	9 points
4	Building form	BF	8 points
5	materials and Resources	MR	34 points
6	water supply and drainage system	(DS&W S)	16 points
7	natural power supply	NPS	15points
8	environmental design process	(EDP)	1 points

See appendix-1

3.5.1 Sustainable Site (SS)

Sustainable site deals with issues outside the building, i.e., the land that is being developed and the surrounding community. Appendix-5 shows the requirements the total points for the sustainable site is, 12 points equal to 10% from 125 points. This 12 points comes from the main content of the sustainable site category contains sub-issues. These are: site selection (1/12) equivalent weight (0.083); construction system (3/12) equivalent weight (0.25); controlling systems (3/12), i.e., parking control, construction activity control and natural water features. Alternative transportation (3/12), i.e., public transportation access, bicycle storage, and low emitting fuel. Improve thermal environment (2/12) equivalent weight (0.16), i.e., maximized open space and enhanced landscaping on site; and the study of the heat island effect (1/12) equivalent weight (0.083). All these sub issues are detailed in Appendix-1 and Appendix-2. For the applied assessment method, each sub issue scores one or two points according to its importance and positive impact on the environment.

3.5.2 Indoor Environmental Quality (IEQ)

The indoor environmental quality (IEQ) portion deals with materials and systems inside the building that affect the health and comfort of the occupants and construction workers. The indoor environmental quality

category of the method of assessment consists of 7 sub issues. See Appendix-1 and Appendix-2 for details on the assessment method, Appendix-5 for the requirements and benchmarks for the main categories of the assessment method of the research. The total points should be achieved are 30/125 which equivalent to 24%; This 30 points comes from the detailed content indoor environmental quality main issues and sub issues. The first issue is the building orientation (4/30) equivalent (0.13) which includes applying the building orientation to the North-South direction (1/30) equivalent (0.03), to East - West direction (2/30) equivalent (0.06). The second issue is to control building dimensions by applying surface volume ratios, which should be between 0.12 to 0.16 to avoid exceeding solar radiation on the building (1/30). The third issue is roof thermal control (5/30) equivalent 16.6%, which includes roof thermal insulation (1/30), white colours (1/30), double roof (2/30), and green roof (1/30). The fourth issue is the study of wall thermal control (12/30) equivalent to (0.40) which includes building materials (1), windows (5) equivalent (0.16), shaded devices (4/30) equivalent (0.13), wall paints and colour (1), and green walls (1). The fifth issue is the study of floor thermal control (1/30); choosing the floor finishing material from an eco-floor material manufactured from recycled construction building materials such as concrete, stones, bricks, ceramics, and has long term of durability, easy to clean, easy to maintain, durable to pressure, non-slippery, heat and moisture resistant. The recycling content is suitable to the most of the residential buildings. The sixth issue is the design of thermal comfort (4/30) is equivalent to 0.13 which includes individual thermal comfort (1/30), controlling the natural ventilation e.g. maximize the windows (1/30), the use of traditional solutions such as wind tower (1/30) and the courtyard system (1/30) that improves the air movement and air temperature in buildings. The seventh issue is supporting these solutions by mechanical means (3/30) equivalent to 0.10 such as using of fans, desert coolers or HVAC systems, which help in controlling the air temperature, air humidity and filtering the air from dust. These solutions vary in different residential areas. However, the use of air conditioning system is evaluated as -1 points because it has negative impact on the environment. Each sub issue scores one or two points according to its importance and positive impact on the environment.

3.5.3. Outdoor Thermal Control (OTHC)

The researcher added the outdoor thermal control category. Table 1 in Appendix-1 includes the details of the sub issues of outdoor thermal control category. The total points achieved is 9/125 points equivalent to 7% , this number comes from detailed issues and sub issues of outdoor thermal control category. Each sub issue scores 1/7 equivalent to 0.14 or 2/7 points equivalent to 0.28 according to their importance and positive impact on the environment. People in Greater Khartoum are aware of the outdoor environment because the climate is hot and dry. They spend part of their time, especially at nights, in the gardens, which are also utilized during

holidays and celebrations. The first issue is to provide shades to the building in the North-South direction (2/9). The second issue is to provide shades to the East-West direction (1/9). The third issue is to provide shades using balconies (1/9). The fourth issue is to enhance landscaping on site using plants and trees that provide shades (1/9). The fifth issue is to build fences to protect the site from dust (1/9). The sixth issue is to build swimming pools (1/9). The seventh issue is apply fountains to change the dry climate into a humid climate (1/9). Terraces (1/9). See Appendix-1 for the assessment method of the research and equivalent percentage, Appendix-2 for details, and Appendix-5 for the requirements and benchmarks for the main categories of the assessment method.

3.6.4. Building Form (BF)

The building forms category was added to the main five categories by the researcher, because it is important to study the relation between solar angle and building form, and choose the best solution that gives more shades to the building. This helps in cooling the surrounding air of the building. See Appendix-1 for details on the sub issues of building forms. Total points should be achieved are 8. Each sub issue scores 1 point according to its importance and positive impact on the environment.

Although LEED V4 did not add building form as a separate category, Council, U. S. G. B. (2014) stated, "Provide shade from structures covered by solar panels that produce energy used to offset some non-renewable resource use. Provide shade from architectural devices or structures that have a solar reflectance index SRI of at least 29. Implement a maintenance program that ensures these surfaces are cleaned at least every 2 years to maintain good reflectance". This was added under sustainable site category in LEED V4 and LEED V3. Further, Council, U. S. G. B. (2014) mentioned, "Naturally ventilated buildings must comply with a local standard that is equivalent to ASHRAE Standard 62.1-2007".

In my opinion, there is no specific category or sub issue dealing with building forms. It is essential to deal with building forms to control building shades and natural ventilation through building orientation. The total points of building form is 8/125 points equivalent to 6.4 %. This 8 points comes from the detailed sub issue. The research draws details such as linear forms (1/8) equivalent to 0.125, U-shaped forms (1/8), L-shaped forms (1/8), cubic forms (1/8), circular forms (1/8), courtyard systems (1/8), use of vaults (1/8), and use of domes (1/8).

3.6.5 Materials and Resources (M & R)

The materials and resources category has 13 credits with a total of 34 points. See Appendix-1 for details on the sub issues of materials and resources category. Each sub issue scores one or two points according to their importance and positive impact on the environment. Materials and resources consist of 13 sub issues. Total points should be achieved are 34/125 points equivalent to 27%. The number 34 points comes from the detailed issues and sub issue of building material category. The first issue is the material used in

the base like bricks, cement, gravel and stone (6/34) equivalent to 0.176. The second issue is the material used in walls like bricks, stone (9/34) equivalent to 0.264. The third issue is the material used in the roof like cement, bricks and wood (3/34) equivalent to 0.088. The fourth issue is the materials used in finishing's such as wood and carpet (5/34) equivalent to 0.147. The fifth issue is the recycling of building materials such as recycled ceramic (2/34) equivalent to 0.058. The sixth issue is wall claddings (1/34) equivalent to 0.029. The seventh issue is indoor décor (3/34) equivalent to 0.088. The eighth issue is construction waste management (1/34) equivalent to 0.029, the ninth issue is calculating the embodied energy (1/34) equivalent to 0.029, the tenth issue is life cycle analysis (LCA) (1/34) equivalent to 0.029, the eleventh issue is adopting technologies (1/34) equivalent to 0.029, the twelfth issue is applying regional materials like wood and stones (1/34) equivalent to 0.029, and the thirteenth issue is low emitting building materials (1/34) equivalent to 0.029.

See Appendix-1 for the assessment method of the research, Appendix-2 for details, and Appendix-5 for the requirements and benchmarks for the main categories of the assessment method of the research.

3.6.7 Water Supply and Drainage System (WS&DS)

The water supply and drainage system category has 7 credits. The total points should be achieved are 16/125 points equivalent to 12.8%. 16 points comes from the detailed issues and sub issues of water supply and drainage system. See Appendix-1 for details on the sub issues of water supply and drainage system. Each sub issue scores one or two points according to their importance and positive impact to the environment.

The first issue is choosing the appropriate technology for the drainage system (5/16) equivalent to 0.312. The second issue is studying the water source (3/16) equivalent to 0.187. The third issue is water efficiency (4/16) equivalent to 0.25. The fourth issue is rain water container (1/16) equivalent to 0.062. The fifth issue is grey water recycled in the site location (1/16) equivalent to 0.062. The sixth issue is to reduce water usage (1/16) equivalent to 0.062. The seventh issue is to use water sense labelled products (1/16) equivalent to 0.062. A total of 16 points. Most areas of Khartoum in the first and second urban areas use septic tank and well system because there is no net drainage system available in most of these new urban areas. This system (well and septic tank) is connected to an artesian well which is usually about 50 meters in depth underground or until reaching the underground water bed. This system needs regular cleaning to secure continuous water flow and to avoid clogging. Taking into consideration the continuous risks of floods during the raining season, regular maintenance is essential in order to guarantee an efficient system. See Appendix-1 for the assessment method of the research and Appendix-2 for details.

3.6.8 Power Supply System (PS)

The power supply system category 4 credits with a total of 15/125 points equivalent to 12%. The total points 15 comes from the detailed issue and sub issues of power system. See Appendix-1 for details on the sub issues of

the power supply system category. Each sub issue earns one or two points according to their importance and positive impact on the environment.

The first issue is studying the source of energy; an eco-building should provide natural resources such as solar energy and wind energy (6/15) equivalent to 0.4. The second issue is energy efficiency (1/15) equivalent to 0.06. The third issue is studying the applications (5/15) equivalent to 0.33; in Khartoum the sun shining is adequately around the seasons, and can be utilized as a source of power in all buildings for various activities, lighting, cooking, heating, and cooling; storing this energy in batteries. The fourth issue is adaptive technologies, like photovoltaic technologies, using simulations and energy smart panels (3/15) equivalent to 0.20. A total of 15 points.

See Appendix-1 for the assessment method of the research, Appendix-2 for details and Appendix-5 for the requirements and benchmarks for the main categories of the assessment method of the research.

3.5.8 Environmental Design Process (EDP)

The main scope of design is to apply the sustainable categories in the whole design process. The term holism has been used to describe the view that a whole system must be considered rather than simply its individual components, as shown in Fig. 5.2. The Vales have addressed this point in their book "Green Architecture", suggesting that a building should attempt to address all of the principles of green design in a holistic manner (Hide, 2008). Architects should consider the eight categories of the method of assessment of this research to be applied in the design process at all design levels. The total points in this category is one (1/125) equivalent to 0.008.

See Appendix-1 for the assessment method of the research points and equivalent. Appendix-5 for the requirements and benchmarks for the main categories of the assessment method of this research.

(i) Pre building phase:

Pre building phase is the design phase for the primary, developed and final designs; adopting sustainable eco-building categories as its main goals.

(ii) Building phase:

Building phase is for the construction and system operations. In this level one should deal with contractors and suppliers, applying appropriate technologies in mechanical systems, construction of waste disposals, and noise control from site.

(iii) Post building phase:

This level deals with users, after the construction of the building. The building should be maintained regularly in order to guarantee long life and durability. The building should be evaluated using appropriate method of assessment. These levels are identified after a review of the previous methods in chapter five such as (BREEAM, 2014).

< 40 is weak

(40 - 44 pts)	pass
(45 - 59)	good
(60 - 75 pts)	Very good,
(76-132pts or more)	Excellent.

The more points you get the higher building level will be

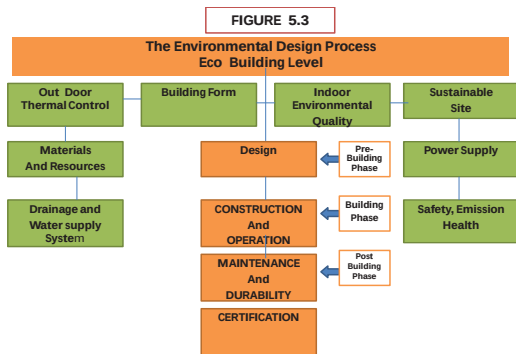


Figure (2): shows the environmental design process on the level of eco building.

Source Abdelmoneim, H., (2017)

4. Field Work

Here explaining the procedures of fieldwork in selected areas of the case studies representing different areas in Greater Khartoum. The duration time of the study from 2015 to 2017. The presenting the fieldwork results. The presentation of the case studies and selected samples and then application of the sustainable-eco-building assessment method sheet of this research (see Apendix-2) made in 48 case studies, and then will give a general summary of information for each case study. The results are presented in figures, tables, pie diagrams and photos.

The survey was made in residential areas in Greater Khartoum, in Khartoum includes Eltaief (10 case studies), Al Sahara middle (8 case studies) and Khartoum Two (5 case studies then in the illegal areas in west Sarya (3 case studies). In Cafori, Khartoum North, (5 case studies), Al Shabia (7 case studies). In Omdurman in Al Rouda (5 case studies) and Al Mourada (7 case studies), the total number of case studies is 48. The method of presentation of these samples in photos, and short notes and documents about each house were written including information about the name of the owner, the plot size, the built up area, construction starting date, construction ending date. Then document is concern about the main categories of sustainable design that identified in chapter two and discussed in chapter six about the energy used, water, material, indoor environment and outdoor environment and the infrastructure. That has been followed by summarizing this information about these specific main categories in tables and figures for each house of the case studies.



Figure 3 :Shows the area of study at Greater Khartoum

5. Conclusion and Findings

5.1 At urban design level: Sustainable site

(i) Accessibility

The research found good accessibility of the first group (El Taief, Kafoori and Al Rouda); the study received a score of 35% for this group, because the plot is near to a public transportation axis. However, the third group (Al Sahafa, Al Shabia and Al Mourada) has poor accessibility; revealed a score of 20%, because the plot is far from the main road, because site selection is according to land distribution from the Ministry of Housing and Urban Planning.

(ii) Site control

Good control in parking covered by shed, noise prevention, and waste management for (El Taief, Kafoori and Al Rouda) has been achieved because, received a score of 65%, because owners and professionals have experienced in such solutions. However, the research found weak control in parking, noise and waste prevention for the third group, revealed a score of 40% because of owners' lack of knowledge and experience.

(iii) Maximize the outdoor

Large open spaces were found for the first group (El Taief, Kafoori and Al Rouda) due to the moderate plot sizes ranging between 400 and 600 sq. m. received a score of 60%. On the other hand, the research found limited plot area in the third group, size (250-300 sq. m)

With a score of 40%, according to distribution land standards for urban classes from Ministry of Urban planning.

(iv) Heat island

Heat island effect is not treated in all samples disclosed a score of 20% because owners have a lack of knowledge and practice in applying such solutions like white paint, green wall and green roof.

5.2 At house unit level

(i) Indoor Environmental quality

Good solutions were found such as roof insulation, building dimensions, windows design, vertical and horizontal sunscreens, and natural ventilation, use of fans and desert coolers, and good orientations, received a score of 33%, because owners and professionals have good knowledge and experience in applying such solutions. Weak solutions are seen in using techniques such as wind towers, courtyard systems and double roofs. It is found that no green walls, green roofs, thermal comfort control, lighting control HVAC systems and occupancy based blinds or curtains are used. This is because people have no experience and knowledge in using such solutions, and HVAC system is expensive. Outdoor environment

For group one (El Taief, Kafoori and Al Rouda), there were good applicable solutions for the outdoors such as shades, terraces, canopies, balconies and vegetation and landscape, received a score of 67%, because of large plot sizes ranging between 400 and 600 sq m. On the other hand, there were weak solutions for group three (Al Sahafa, Al Shabia and Al Mourada) revealed a score of 14.5%, because of the small plot sizes ranging between 250 and 300 sq m. There were non-applicable solutions for third and illegal areas such as swimming pools and fountains because of their limited appreciation of the importance of such solutions to minimize heat. Moreover, these solutions could be costly.

Environmental design process and building form

Weak points for environmental design process for all areas of the study have been found, the study received a score of 33% as average result.

Most of the buildings in the areas of study used linear forms with a received a score of (60%), then cubic forms (19%) and courtyard systems. There were no alternative solutions to SEBAM like vaults, domes (Only case study No. 9), L-shaped forms revealed a score of (11%) (Only case studies No. 8 and No. 47) and U-shaped forms. The reasons could be the high price of plots and the need to maximize built-up area.

5.3 At building construction level

(i) Construction method

Applicable solutions were observed, such as concrete skeleton for the first group (El Taief, Kafoori and Al Rouda) received a score of 57%. Load-bearing systems for the third group (Al Sahafa, Al Shabia and Al Mourada) revealed a score of 44%, and mud bricks in illegal areas by a score of 100% because these solutions meet the residents' needs and are economical. The research found problems in ceiling and poor insulations in the third group.

(ii) Materials used

Concrete ceilings by 57%, bricks or hollow blocks in walls, and ceramic by 67% or marbles by 16.4 % on floors have been used for the first group. Wood and zinc on ceilings 32%, bricks on walls, and recycled ceramic on floors by 12% have been used for the third group. Sand, gravel and clay blocks for the illegal areas are found, because owners and professionals use materials available in the local environment

(iii) Solutions that are not found

Applicable solutions such as waste management, roof clay tiles, wall cladding, glass, aluminium and wood were not found. The reason for not using wood, roof clay tiles and cladding is that they are expensive and not available in the local market. Limited solutions are found in recycling materials because of lack of knowledge in using such recycled materials, especially in the first group.

5.4 At the building services level

(i) Water

All case studies: the water comes from the National Grid. The research shows unsuitable solutions in using biological treatment, rainwater containers, water metering system, water recycling, and water efficient products because residents cannot afford to use such solutions.

(ii) Drainage system

All the case study samples in El Taif, Kafoori and Al Rouda neighbourhoods used septic tanks and wells the research received a score of 75% in a drainage systems. These drainage provisions could contaminate the underground water. Khartoum 2 neighbourhood uses a drainage network by 100% in sewage system. However, in Omdurman, some buildings still use the Pit latrine received a score of 12.5%; and in illegal housing areas, sand and gravel filters are used by 100%.

(iii) Energy

The research obtained a result of, all case study samples use energy from the National Grid. By 100%. There are few alternative solutions for SEBAM in using solar energy, energy heating system, outdoor lighting and solar heating. Only case study No. 5 used solar heating and case study No. 9 used solar PV cells. The research shows that there are unsuitable solutions in wind energy and solar boiling because people do not have experience in using such solutions and they are expensive.

Recommendations regarding the samples studied by the proposed method of evaluation:

6. Recommendations

6.1 At urban design level: sustainable site

- (i) The research recommends creating accessibility to all plot areas which should be near to a public transportation axis.
- (ii) The site should have parking control, covered by sheds, construction activity control, noise prevention and waste management.
- (iii) The site should have good landscape management and outdoor lighting control.
- (iv) Heat island effect should be studied by plant trees and use light colours.

6.2 At house unit level

(i) Indoor environmental quality

The research strongly recommends effective solutions for natural ventilation, the use of horizontal and vertical sunscreens, and the use of mechanical means such as desert coolers and fans to improve the thermal comfort inside the building. In this study, orienting the building towards the East-West direction, the use of wind towers, the use of courtyard systems, and the implementation of light colour

paints on ceilings and walls is recommended. Moreover, in this research, adopting solutions such as double roofs, green roofs, green walls, floor thermal control, design thermal comfort and lighting control are suggested.

(ii) Outdoor environmental quality

Maintaining open spaces at the house unit level, controlling shades by the building construction like cantilever and canopies and fences in the outdoor environment are recommended in this study. Adopting swimming pools, fountains, terraces, trees and vegetation cover to improve the air from dry to humid in all areas of the study is proposed.

- (iii) Environmental design process and building form, applying of environmental design process in the three phases as an educational value is strongly recommended in this study. Using the linear and cubic forms, vaults, and domes is proposed in this study. Applying L-shaped and U-shaped forms in sustainable-eco-buildings is also suggested because they provide more shades to the building and this cools the air through the building and improves ventilation.

6.3 At building construction level

(i) The use of eco concrete, eco structure, and thermal hollow blocks to all case studies and managing the ceiling structure and insulation for the third group is recommended in this research.

(ii) Building Materials should be used from the local environment like bricks, ceramic and stones because it will be economic. Also, the using of wall cladding with special specifications, and adopting steel, hollow blocks, recycled materials, eco carpets, and suspended ceilings is proposed in this study.

(iii) Using of recycled building materials, especially for the outdoor area, is recommended in this study.

6.4 At services level

(i) Water system

The research recommends adopting water metering system, biological treatment and applying water efficiency.

(ii) Drainage system

The research recommends adopting distribution network for sewerage systems or otherwise maintaining and minimizing the use of septic tanks and wells, as they are contamination threats to the underground water. In addition, solutions such as recycling of grey water, and rainwater containers are recommended in this study. For illegal housing areas in West Sarya, using wells and septic tanks as "best practice" and network as future solution for drainage system is suggested in this study.

(iii) Energy efficiency

In this research, applying natural resources for energy such as solar energy system in different applications, solar heating, solar cooking, solar photovoltaic technology is proposed. The use of stimulations, the use of smart panels, and wind energy especially for suburb areas is recommended. For illegal housing areas in West Sarya, power supply to be supplied by the National Grid is proposed.

(e) At community level

The research strongly recommends adding educational value to increase the knowledge of the community and teach the students, architects, designers and people about sustainable- eco- building through lectures, workshops, conferences and courses corresponding to its main categories.

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Effect of various surfactant and innovative techniques on dispersion of carbon reinforcement in cement-based materials

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Abstract:

Comparative studies on dispersion of two Carbon Fibers (CFs) types using surfactants like water, acetone, Glenium 3030 & 7101 and methyl-cellulose has been conducted in this paper. Sonication probe, magnetic stirrer and high shear homogenizer have been used and shown to dramatically increase dispersion efficiency of CFs. After selecting the most reliable and practical dispersion method, mechanical behavior of CFs reinforced mortars has been also investigated with dosage at 2, 2.25 and 2.5 wt% of cement. Dog bone shape specimens were tested in early age under direct tension in order to evaluate the mechanical properties such as ultimate load, deflection criteria, and load - deflection behavior of CFs reinforced composites while cubes were also prepared to determine the compressive strength of these composites. These results have been compared with each other and with the result of plain/control cement mortar specimen.

Keywords:

Dispersion of Carbon Fibers, Tensile Strength, Compression Strength.

1. Introduction

Civil infrastructure is heavily dependent on cementitious material like concrete and mortar. Cementitious materials are likely to be quasi brittle material and having a low tensile stress-strain property. The deterioration of the civil infrastructure across the world has led industry to focus on improving the mechanical properties and durability of cement-based materials. To overcome these weaknesses and to make structures using these materials multifunctional, Carbon Fibers can be introduced in cementitious matrices. Cement, concrete and mortar are widely used in construction industry rather than polymer composites in the form of structural and non-structural elements because of their compressive strength, durability, versatility, low maintenance, affordability, fire-resistance, thermal mass and albedo effect. Thus, several studies incorporating Carbon Fibers in cementitious material have been carried out all across the globe. Incorporation of Carbon Fibers in cement composites increased tensile strength, modulus and ductility (in terms of compression, tension, flexure or torsion) decrease electrical resistivity and drying shrinkage. It can also contribute to high specific heat, low thermal conductivity, high corrosion resistance and low thermoelectric behavior of the materials. [1,3] as well as controlling cracks. Moreover, CFs are used in conventional fiber reinforced concrete and have been found to be ideal reinforcing materials. These fibers are also the suitable materials for retrofitting and strengthening purposes. [3] While exploring various applications of carbon fibers in cementitious material, it is already clear that the science of adding the tiny fibers is making big changes and resulting in economic benefits for the construction industry.

However, nanocomposite materials have strong tendency to agglomerate due to the presence of attractive forces which is known as Van der Waals effect [2,3,8,9,10]. Due to this force, use of CFs results in the formation of entangled ropes and clumps which are very difficult to disentangle [2]. This effect strongly affects the dispersion property of fibers. Because of poor dispersion there may be many chances of defects in nanocomposites. Insinuation of agglomerates with cement matrices is arduous. Subsequent distribution of material within matrices or solvent or the process of deagglomeration is known as dispersion. The evaluation of fiber dispersion has seen greater attention and has become a hot topic. Various chemical techniques have been used to get homogeneous dispersion of CFs in water or directly in cement composition using Acrylic, methyl-cellulose or latex as admixture [4] or using surface treatment like H_2SO_4 AND HNO_3 and oxidation is done by reflux or sonication [2] or by using polycarboxylate-based superplasticizer [5]. The dispersion behavior of Carbon Fibers depends on a few carping factors like attractive forces, length of fibers, viscosity of matrices and density of fibers. [10] On the other hand, physical methods have also been used to achieve good dispersion like magnetic stirrer, homogenizer and sonication techniques. Among all of these, sonication method is consummately used [2,3,5,6,8,9]. In fact, long period of sonication is harmful because it can cause breaking and shortening of fibers [2].

Moreover, the same critical issue is with incorporation of carbon fibers with cement matrices. The dispersion of CFs is not feasible while mixing cement paste as cement paste settling starts within short duration just after adding water. Conventional method of mixing

cement paste would lead to improper dispersion of CFs and they will be in agglomerated form. To avoid this situation common strategy is to mix CFs in water and make sure it is dispersed well and then add it to conventional mortar mixer with cement and sand. Serious difficulty like negative effect of many surfactant (adequate for dispersion of CFs and CNTs) during cement hydration can be observed. [2] Method of dispersion should be carefully selected to avoid interference on hydration process of cement. Some surfactants may react with cement paste and create air void in mix or lower down the strength and lead to poor result. Size difference between cement particle and CFs can cause poor result so the gap between these two particles should be filled up, which lead to use of silica fume. Use of small size cement particle can cause high water consumption and lead to drying shrinkage. To minimize this effect, use of other cementitious material such as CFs, CNTs, glass fibers, polypropylene fibers or most of the fibers could be a good option. Due to small particle size of silica fume, it helps in dispersion and improvement of interfacial bond between the CFs and the cement hydrated paste [9]. It was reported that comparing optical images of dispersions (good dispersion) with SEM images of the CFs cement paste (bad dispersion), that obtaining good dispersions of CFs in water with surfactants does not guarantee a correct distribution of the CF in the cement matrix [8].

Studies have shown that CFs can improve mechanical properties such as tensile strength, but it is still extravagant to use in larger concrete structures such as bridges, dams and buildings. There is a wide range of results concerning mechanical properties: from huge increments (even though the dispersion obtained was inhomogeneous), to no variations. Undoubtedly, the type of CFs and its dispersion in the cement matrix play an important role [8,10]. Acrylic, methylcellulose, acetone, hydroxyethyl cellulose, latex, styrene acrylic, polycarboxylate based and various dispersion agent have been used as an admixture to modify cement based material [2,3,4,5,11]. Water/ cement ratio was in the range of 0.32 to 0.527. [2,3,4,5,11,12]. CFs 0.5% by weight of cement together with dispersant, chemical agent and silica fume, in concrete with fine and coarse aggregate were used and increased in flexural strength by 85%, flexural toughness by 205%, compressive strength by 22%, material price by 39% and increase in freeze & thaw durability were noticed [12]. The behavior of plain cement mortar composite round bars with random distribution of CFs (2.25% by weight of cement) increased the tensile strength by 38% compared to plain bars. In this paper dispersion property, compressive and tensile strength of carbon fibers are addressed.

2. Experimental Method:

The experimental investigation reported here targeted at studying the dispersibility of Carbon Fibers in aqueous solution and cement paste. Various dispersing agents were used like water, acetone, and commercially available concrete admixture such as Glenium 3030, Master Glenium 7101 and methylcellulose. Two types of CFs, called type W and B (name given by author), were used in the mixture and their general properties are summarized in Table 1. Sonication probe, magnetic stirrer and high shear homogenizer have been implemented for different time duration to observe changes in dispersion of CFs. To understand suspension of CFs in aqueous solution, silica powder and multi-walled carbon nanotube have been also utilized.

Table 1: General Properties of Carbon Fibers

Tensile Strength	4137 MPa
Tensile Modulus	242 GPa
Electrical Resistivity	0.00155 ohm – cm
Fiber Diameter	7.2 microns
Fiber Length (nominal)	3,6 & 13mm
Carbon Content	95%
Moisture content	0.5% maximum
Unpacked Bulk Density (minimum)	350g/L

Portland Cement (Type 1 as per ASTM C150 [15]) was employed as the binder with specific gravity of 3.15. Locally available natural sand was used at cement to sand ratio of 0.5. Silica Fume was used by replacing 15% weight of cement. The water/cement ratio was 0.45. Master Glenium 7101 was used as water reducing agent (WRA) and as a dispersing agent. Quantity of WRA was 1% by weight of cement. Table 2 describes proportion for aggregate for 1m³ of quantity. Dosage of 2, 2.25 and 2.5% by weight of cement were selected for both CFs types. Properties of fine aggregate have been described in Table 3.

Table 2: Mix proportion

Cement (kg/ m ³)	Sand (kg/ m ³)	Silica Fume (kg/ m ³)	Water (kg/ m ³)
492.8	1314.15	98.56	295.68

Table 3: Property of Fine Aggregate

Specific Gravity of Sand	2.651
Fineness modulus of fine aggregate	2.8
Moisture content of F.A.	4.11

Master Glenium 7101 was dissolved in water and stirred by hand for about 2 minutes. CFs were added in the solution and magnetic stirrer was used for about 20 minutes. Afterward, an ice bath was prepared and the specimen was kept in the bath for 30 minutes and later in the sonicator for another 20 minutes keeping 50% amplitude and imparting 20 second pulses with a gap of 20 seconds. Then the weighed cement, sand,

silica fume and dispersed mixture were added in a rotary mixer for 5 minutes. After pouring it into oiled molds, mechanical tamping has been done to consolidate and decrease the amount of air bubbles. The samples were demolded after 24 ± 2 hours and cured in water bath for 7 and 28 days.

Compressive strength was measured on cube samples of size 50 mm using Forney Compression testing machine following ASTM C109 [14] procedure. Dog bone shaped specimens as shown in Figure 1 have been used for uni-axial tensile testing. Samples were tested according to ASTM C307 [13] on a loading frame with 5.24 mm/min cross head movement. Three specimens of each composites were tested under compression and tensile loading at age of 7 and 28 days.

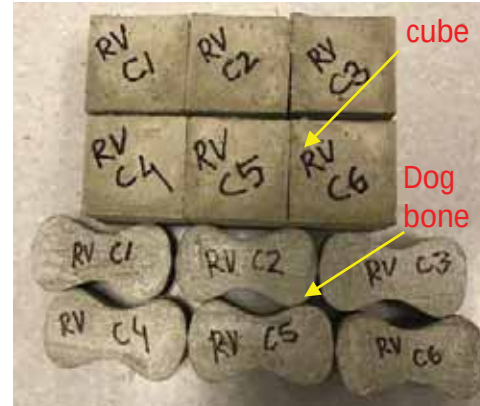


Fig 1: Casted Specimen

3. Results and discussions

In this paper dispersion process and effect on dispersion of CFs using different surfactants has been described. In later part of result, discussion of mechanical property like compressive strength and tensile strength has been overviewed. Behavior of surfactants and CFs in different aqueous solution has been described in Table 4.

Table 4: Effect of surfactants on different materials

Sr. No	Type	Content (gm)	Dispersing Agent	Magnetic Stirrer	Sonication Probe	High Shear Homogeniser	Result
1	W	0.2	Water	60min	no	no	Clotted (Fig 2a & b)
2	W	0.2	30% acetone + 70% water	15min	No	2min	After magnetic stirrer neither clotted nor dispersed All particles crushed after using high shear homogenizer. (Fig. 3 a & b)
3	B	0.2	Water	60min	30min	2min	Swelling of fiber was visible after magnetic stirrer. No visible effect of sonication. somewhat chopped after using high shear homogenizer (Fig. 4)
4	B	0.2	Water+ 0.05gm MWCNT	60min	30min	2min	Formed gel type. Suspension of CFs and MWCNT is visible. (Fig.5)
5	B	0.2	Water+ 2gm Silica powder	60min	30min	2min	Suspension turned into Grey colour for long time. (Fig.6)
6	W	1	100mL water+ 5gm of 3030	20min	20min	no	Swallowed and in clotted form
7	B	1	100mL water+ 5gm of 3030	20min	20min	no	Most of them in clotted form
8	W	1	100mL water+ 5gm of Methyl cellulose	20min	20min	no	It was not dispersed when added in solution. After sonication in good dispersed form. (Fig. 7)

9	B	1	100mL water+ 5gm of Methyl cellulose	20min	20min	no	In suspension for a while. Good effect of sonication. (Fig. 8a & b)
10	W	1	100mL water+ 5gm of MG 7101	20min	20min	no	Visually dispersion is same like as if used Methylcellulose. Good dispersed. Created bubbles in it as if added soap water, they act as air entraining agent as well water reducing agent. (Fig. 9 a&b)
11	B	1	100mL water+ 5gm of MG 7101	20min	20min	no	After dispersion, they are apart from each other but in solution they were agglomerated. Bubbles are like w type. (Fig. 10 a&b)

The effects on the dispersion of CFs using surfactant or without surfactant have been shown in following figures. Figures 2 to 10 represent various dispersion methods conducted in this study and indicate that the solution generally contains large clumps of entangled CFs with only some portion of CFs floating individually in water. The sonication period has not been long enough to disentangle CFs and clumps of CFs are visible. Long time of sonication may cause breakage of fibers so the time used in this study is suitable for sonication. Similar pattern of agglomeration could be observed when surfactant is not enough or surfactant could not break hydrophobicity of CFs. When silica fume was used individually or combined with methylcellulose (or MG 7101), it helped in the dispersion of fibers.

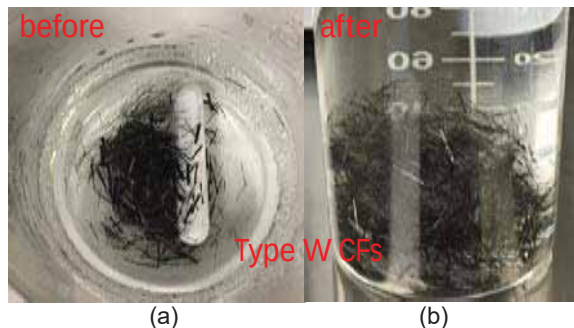


Fig 2: W type of CFs in water as a surfactant. (a) before dispersion & (b) after dispersion

Method 1: Figure 2(a) shows there is no effect on type W fibers when only water was used, whereas figure 2(b) shows that it slightly gets dispersed in water due to magnetic stirring.

Method 2: Figure 3(a) exhibits that using same type and amount of type W fibers (similar to figure 2) in acetone instead of water, their physical appearance is completely different due to chemical reaction. Fibers

are swollen once they were dispersed in the acetone as shown in the figure 3(a); however, they didn't reveal much changes in their appearance after magnetic stirring. (

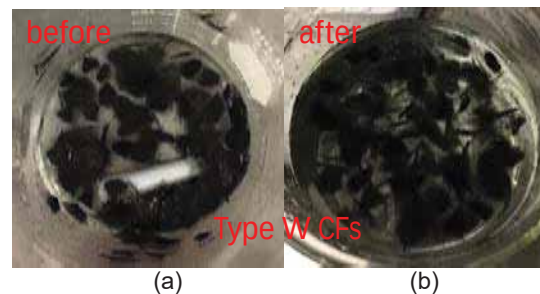


Fig 3: W type of CFs in solution of water + acetone as a surfactant. (a) before dispersion & (b) after dispersion

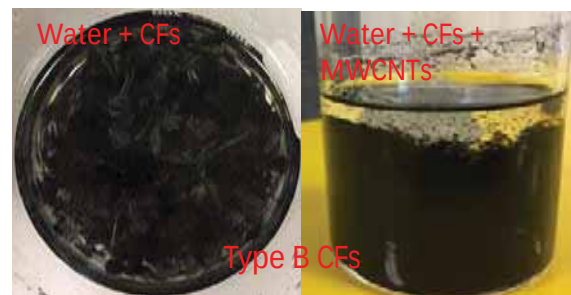


Fig 4: Type B CFs in water

Fig 5: gel type
(in suspension)

Method 3: In comparison to type W fibers, Figure 4 shows that type B fibers broke down into individual fibers after magnetic stirring and changed its volume to more than double which means that the fibers were disentangled from each other. When high shear homogenizer was used, fibers were completely

crushed into small particles. This looks like that milled fibers are present in water.

Method 4: when a very less amount of MWCNT was added to half of the mixture which was made for method 3 (Figure 4), MWCNTs filled the gap between fiber particle and the solution became like a gel and it lasted in suspension for a long period of time (in days).

Method 5: Similar to method 4, once silica powder was mixed in another half of the mixture which was made for method 3, it changed the mixture's color to grey and lasted in suspension for days as shown in Figure 6. The outcome was not very different when Glenium 3030 was used as surfactant.

Method 6: As one type of surfactant, Methylcellulose also exhibited well dispersion for type W fiber after sonication as represented in Figure 7.

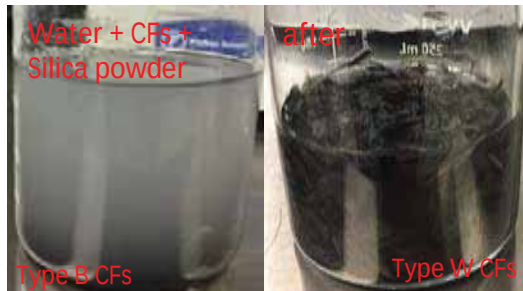


Fig 6: suspension in Silica powder

Fig 7: After Sonication of CFs



Fig 8a: Type B CFs before dispersion in solution of Methylcellulose and water

Method 7: Similar like method 6, When Type B CFs are added into aqueous solution they are separated much better compared to W type of CFs as shown is Figure 8a.

As shown in Figure 8b it looks like Type B fibers are in a clump form in solution but they are dispersed which means they are disentangled from each other.



Fig 8b: After Dispersion process

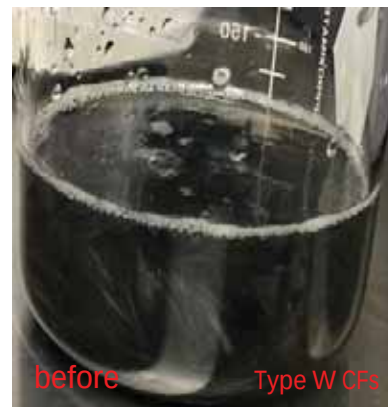


Fig 9a: Before Dispersion of CFs in solution of water + Master Glenium 7101

Method 8: In solution of MG 7101 W type of CFs also get dispersed well as represented in Figure 9a. Figure 9b and 10b clearly show good air entraining property and good dispersion capacity of MG7101. There is a vast difference in CFs before and after the dispersion process has been applied. Though fibers did not fully dispersed, sufficient uniformity in the solution was observed.

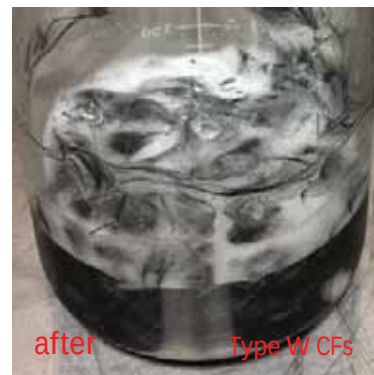


Fig 9b: After Dispersion CF in MG 7101



Fig 10a: Type B CFs before dispersion in MG7101



Fig 10b: Type B CFs after dispersion in MG 7101

Moreover, further investigation should be carry out using SEM or Optical Microcopy or Transmission Electron Microscopy(TEM) or UV- visible spectroscopy to get more clear result of actual dispersion of CFs.

Tensile test was carried out on the dog bone specimens using the MTM machine (Figure 11); compression test has been carried out using Forney machine. Ultimate load and maximum deformation were recorded for each specimen; the average value of three specimens was taken from testing to obtain compressive and tensile strength of CFs reinforced mortars. Table 5 shows the notation given for the different mixes containing different dosage and Table 6 summarizes the average ultimate tensile strength of various mixes for 7 days curing and graphical presentation of average direct tensile and compressive strength is shown in Figure 12 and 13 respectively.

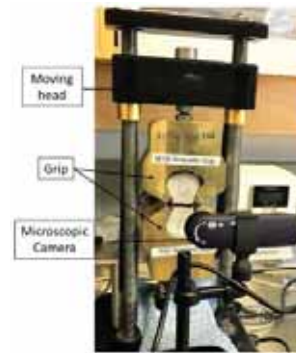


Fig 11: MTM machine for tensile testing of Dog Bone sample

Table 5: Specimen Reference

Sr. No.	Specimen Reference	Constituents	Percentage of CFs
1	C	Control	0
2	B2%	B Type	2
3	B2.25%	B Type	2.25
4	B2.5%	B Type	2.5
5	W2%	W Type	2
6	W2.25%	W Type	2.25
7	W2.5%	W Type	2.5

Table 6: Test Results

Sr. No	Specimen Reference	Ultimate Comp. Stress (MPa)	Ultimate Tensile. Stress (MPa)	Maximum Deflection (mm)
1	C	21.55	4.56	0.87
2	B2%	32.40	5.04	1.01
3	B2.25%	24.20	4.08	0.86
4	B2.5%	20.29	4.00	0.92
5	W2%	28.89	4.49	2.11
6	W2.25%	33.81	3.42	0.91
7	W2.5%	33.61	4.22	1.29

From Figure 12, it can be observed that there is an increase in the tensile strength of dog bone sample containing 2% type B of CFs by weight of cement compared to control mortar. It indicates that presence of carbon fibers in mortar plays a major role in increasing tensile strength. In fact, strong interfacial bonding between the fibers and matrix resulted in efficient stress transfer when strain is applied on a specimen. In other matrices which contains CFs at different dosages show less strength values than the control one due to insufficient dispersion or poor interfacial bond.

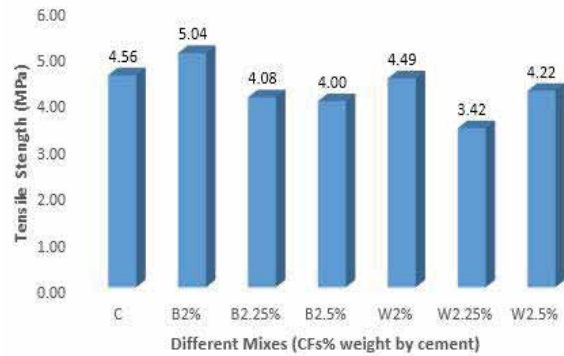


Fig 12: Ultimate Tensile strength of composite mortar Specimen subjected to direct tensile stress.

It is seen that mortar with random distribution of carbon fibers, that is, 2% by weight of cement increases the tensile strength by 10% compared to control mortar, whereas in other cases of 2.25% and 2.5 % decreases the tensile strength by 10% and 12% respectively compared to control mortar in the case of type B CFs reinforced mortar. On top of that, there is also decrease in strength of type W CFs compared to control mortar.

Table 6 shows the seven day curing results of cube for compression test. Silica fume played an important role in increasing the strength.

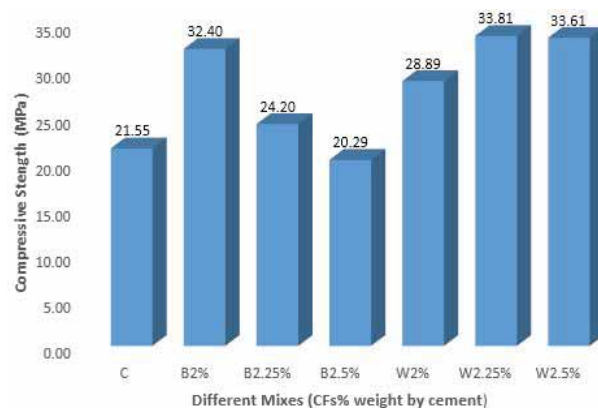


Fig 13: Ultimate compressive strength of composite mortar

It is seen that mortar with random distribution of carbon fibers, that is, 2% and 2.25% of B type (CFs) by weight of cement and 15% replacement of cement by silica fume increase the compressive strength by 50% and 12% respectively whereas there is decrease in the strength when 2.5% of CFs has been used compared to control mortar. Moreover, there was increase of 34%, 57% and 56% when type W CFs has been used in amount of 2, 2.25 and 2.5% respectively.

Load versus deflection graph is shown in Figure 14 for 2% of B type CFs in the mix, but there is existence of slip in the test grips so deflection may contain errors.

The concave shape in the starting part of graph is due to insufficient grip. So, maximum deflection is not just the deflection of specimen but deflection with containing error which can be clearly seen in the Figure 14. The graph is not true representation of ideal load versus deflection graph in general case.

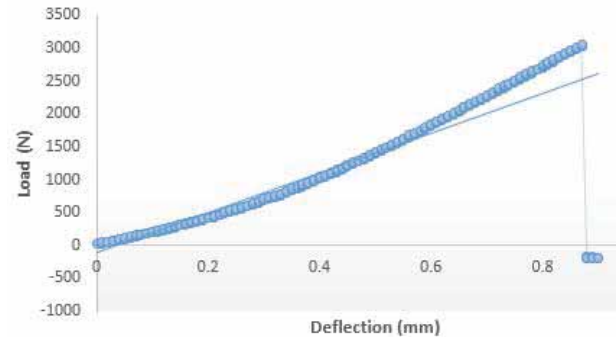


Fig 14: Load versus Deflection Graph

4. Conclusions

Based on tests performed here on fiber reinforced mortar with an average expected compressive strength of 50MPa at 28 days, the following conclusions may be drawn:

While the addition of fibers and silica fume enhance the compressive strength of the matrices.

1. The addition of fibers could increase the tensile strength of the mix and it does in several other cases but the result shown in this paper shows some controversy due to several trial dispersion methods or some different reaction may occur during mixing procedure; thus, created adverse effect on the mixture properties
2. It was found that superplasticizer Master Glenium 7101 could properly disperse a relatively high concentration (more than 2%) of the fibers in water.
3. Hardened cement paste revealed the presence of bundles, clumps, and distribution non-uniformities This suggests that some of the fibers reaggregate during and after mortar mixing. Reagglomeration can be due to the adsorption of water by cement from dispersion.
4. Need further investigation on tensile strength and compression strength of CF reinforced composite material at later age of curing and using other dispersing agents or techniques and dispersion of CFs can be investigated using electronic techniques using SEM or any other method.

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Carbon footprint of citizen consumption in Canadian metropolitan cities

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Abstract:

The carbon Footprint subcomponent of the Ecological Footprint is the dominant impact of the consumption of citizens in Canadian cities. In this study, the household consumption is categorized according to the classification of individual consumption according to purpose (COICOP) for 15 Canadian cities according to census metropolitan areas (CMA). The Ecological Footprint (EF) is calculated from big datasets from international agencies. The EF of CMAs was calculated from the consumption land use matrix (CLUM) of Canada, by scaling results according to the annual national Survey of Household Spending from 2010 to 2015. The expenditure in electricity was also scaled with the carbon intensity factor from Environment Canada. The carbon Footprint associated with housing varied significantly with the source of electricity production. CMAs relying on renewable energy sources have a substantially lower carbon footprint than those relying on fossil fuel energy. The operation of personal transportation was the second-largest contributor to the carbon footprint. Financial services is the largest share of the carbon footprint from service consumption, while also presenting more year-to-year variability in some CMA. In the good category, clothing consumption caused most of the carbon footprint. The food carbon footprint has the same magnitude as the one from goods and services. A better understanding of Canadian needs and promoting local consumption can improve carbon mitigation and long-term sustainability in cities.

Keywords:

Ecological Footprint, cities, housing, transportation, good, services, food

1. Introduction

The Ecological Footprint (EF) is a measure of human demand on natural resources and services. Based on the ecological concept of carrying capacity, EF was introduced and developed as a practical measure of the bioproductive area required to support societal metabolism for a given set of human consumption activities [1-3]. The indicator allows understanding sustainability of cities [4] and regions based on the needs and supplying in renewable resources. More recently the EF allows to identify the sustainable quadrant to reach sustainable development goals (SDG) [5]. Developed countries like Canada should aim to keep their high human development index with a lower EF.

To calculate the city's EF the two approaches are bottom-up and top-down. The bottom up methodology follows uses production, import and export data[6], specific to the local population and boundary such as city or region border [7]. The consumption Footprint is the sum of production and imported Footprints, after deducting exported Footprints. The top down methodology is based on a scaling of national EF results, based on National Footprint Account and country statistics [8]. In the top down approach, the data collected on the consumption patterns of the local population allows to scale the EF, according to consumption categories based on the ratio of local to national average data. In Canada, luckily detailed the consumption data is available, while it is not the case

in every country. Local energy intensity allows considering carbon emission according to energy sources in the different provinces.

The EF of Canadian cities was reported by Wilson and Anielski [9], who estimated EF for 20 Canadians' cities based on average household expenditures data and the matrix of EF components of Canada. The top down assessment was based on a national footprint results prior to the update of the NFA methodology [8], and directly applied expenditure data to scale EF components. An EE-MRIO model was then applied to derive a matrix of consumption category footprints and their respective land use footprints (CLUM), to which expenditure data can be more accurately and consistently applied to scale the NFA. Since this first study, both national [8] and subnational methodologies have been updated and follow a set of proposed common standards.

As carbon is linked with global climatic variation, sustainable cities must find way to reduce the carbon emission from their activities. This paper shows the outcome of the EF methodology to identify the component of consumption more associated with carbon emission in 15 Canadian cities. Here we focus on the carbon Footprint subcomponent and further analyze disaggregated components of CF by consumption category in order to identify target areas for climate change mitigation. The originality of this study is the application and framing of urban sustainability solutions from the carbon component of

the EF. The consumption data is based on the Canadian national survey on household spending for six years. This study remains a proof of concept to apply the ecological footprint indicator to Canadian cities with a top-down approach. A bottom-up analysis ecological footprint of Vancouver was previously conducted [7, 10]. This top-down analysis also allows comparing top-down and bottom-up approach.

2. Methodology

The data analysis required a three-step process: National Footprint Accounts, environmental extended MRIO analysis and scaling procedures at the city level. Ecological Footprint data on production from the National Footprint Accounts (2016 Edition) were used to as input to a footprint extended MRIO model based on the Global Trade Analysis Project (GTAP) 9 database [11]. The resulting Ecological Footprint categorized into final demand in 57 economic sectors and across from GTAP 9 is then translated into COICOP consumption categories from which the national CLUM of Canada is derived. To maintain consistency, 2011 data were used as input data from the NFA in conjunction with 2011 economic data from GTAP 9. Here we follow a top-down approach to estimate cities' EF starting with the national CLUM of Canada. We then scale the national data to each city using average household expenditures, as [9] and CO₂ intensity through energy factor. Using the base year of 2011, we calculated the EF of cities using supplemental scaling data from 2010 to 2015.

The 15 city boundaries are defined according to their census metropolitan area (CMA), closer to the regional boundaries for some cities. They are located in the 10 provinces (ordered from east to west): St John's, Halifax, Charlottetown, Saint John, Quebec City, Montreal, Ottawa-Gatineau, Toronto, Winnipeg, Regina, Saskatoon, Edmonton, Calgary, Vancouver, and Victoria. In the remaining of this article, Ottawa-Gatineau is noted as Ottawa. The number and size of CMAs available in the national Survey of Household Spending (SHS) is limited by the sample design from Statistics Canada. Their goal is to obtain estimates of similar quality across all provinces, but not for all CMAs in Canada. Because of this technical limitation, the CMAs available are not the largest in Canada. The 15 CMA represent the capital cities of the provinces and of Canada to have a provincial outlook, then the cities in economic importance.

For the analysis of 15 Canadian cities, the CLUMs are scaled with the detailed personalized CMA's household consumption statistics collected at the annual national Survey of Household Spending (SHS) from 2010 to 2015, reclassified accordingly to the COICOP categories. The scaling procedure includes adjusting the households' expenditure with the consumer price index (CPI) available for each city [12]. The heating consumption of a province is scaled in terms of its CO₂ intensity [13]. The variability in the figures indicate the standard deviation of the data on

the y axis for 2010-2015, calculated by a simple standard deviation. While the subcategories are presented, the standard deviation is reported on the total. The CMA with less variation means that the population surveyed was more homogeneous, while more variation suggests more heterogeneous consumption habits over the years. Details of the calculation are found in [14]. In a future study, we would like to report on the variability between years by incorporating the survey bootstrap weights.

3. Results and Discussion

In the 15 CMA, the total carbon Footprint is due 33-67% to personal transportation, 2-52% to housing energy, 6-15% to services, 5-13% to good consumption and 3-9% to food, taking here the year 2013. For most cities, personal transportation is the main component of CF. Nevertheless, six cities stand out: Halifax, Saint John, Regina, Saskatoon, Edmonton and Calgary have a CF associated to housing between 2.03 (Saint John) and 4.22 gha per capita (Calgary), whereas for the other cities, housing represents only 0.11 (Quebec) to 0.44 gha per capita (Ottawa) (Figure 1). For these six cities, housing is the largest component of CF. Our study attempts to explain these differences. Starting with analysis cities CLUM, in the category housing, the subcategory 'Electricity, gas and other combustibles' makes the difference. In fact, for Halifax, Saint John, Regina, Saskatoon, Edmonton and Calgary, this subcategory represents 94.87 % (Saint John) to 96.30 % (Calgary) of housing CF total, and is analyzed in more detail in the following sections.

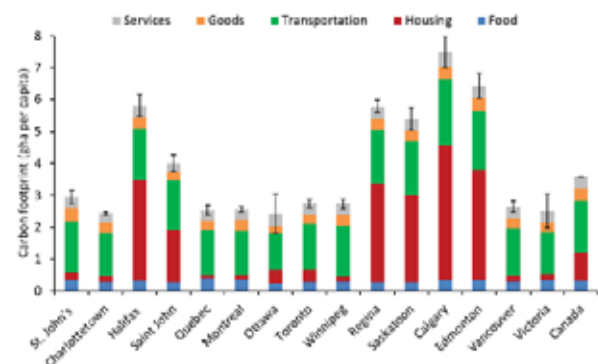


Figure 1: Carbon Footprint of the 15 CMA, average for 2010-2015

"Electricity, gas and other combustibles" consumption category creates the biggest gap between cities. They have either a high CF associated to the category or a very low (near zero), although average expenditures are not very different. Cities getting electricity from fossil fuels mostly (coal, natural gas) have high energy factor. For instance, energy factor of Calgary is 4.88 (the biggest of the 15 Canadian cities), its CF' is 4.08 gha per capita, also the bigger of the 15-Canadian cities. The analysis of power sources in the 15 Canadian cities showed that cities having a carbon

Footprint of 2-3 gha per capita (Halifax, Saskatoon, Regina, Calgary, Edmonton, Saint John) use non-renewable energy to produce their electricity (coal, natural gas, oil) (Figure 2). Other cities (Québec, Montréal, Winnipeg) use only renewable energy, hydroelectricity mostly; thus their carbon Footprint is about 0.01 gha per capita, making it 400% smaller. For Vancouver and Victoria, the energy scaling factor was the factor of the province of British Columbia, with a higher proportion of hydroelectricity. However, the actual energy consumption in cities contains more natural gas. The results will be updated in the next version of the study, based on the proportion of the expenditure in natural gas and the corresponding energy factor. The electricity source, whether renewable or non-renewable, significantly affects the cities' carbon Footprints.

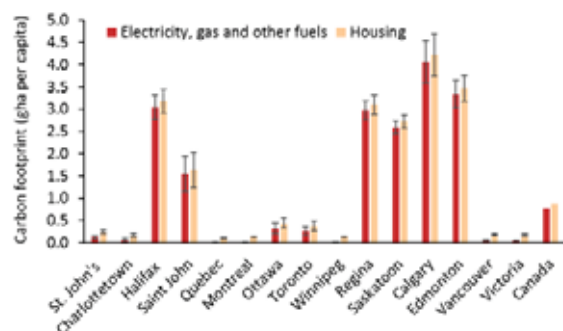


Figure 2: Carbon Footprint from housing

Carbon Footprint of personal transportation is strongly dependent of the use of personal vehicle and transport service (Figure 3). Cities with greater household purchase of fossil fuel (gasoline, diesel oil) have a bigger carbon Footprint for the category operation of personal vehicles. On average, use of personal vehicles represents 60% of the transport category and the subcategory transport service represents about 30%. This trend is changing in Ottawa and Victoria, which have a larger proportion of Footprint in 'Transport services' compared to 'use of personal vehicles'.



Figure 3: Carbon Footprint from transportation

The service category is made of 18 CLUM subcategories; Figure 4 shows the most important ones. The total service CF varies from 0.27 gha per capita in St John to 0.47 gha per capita in Calgary. The average service CF for the 2010-2015 period is $0.36 \text{ gha} \pm 0.04$ for the 15 CMU. Financial services is the dominant source of carbon impact, from 0.17 gha per capita in Calgary to 0.07 gha per capita in St. John's. The variability in financial services expenditure is higher in Victoria and in Ottawa. Victoria and Vancouver have higher expenses in services per capita, while the service consumption has a lower Footprint, which can explain the lower EF.

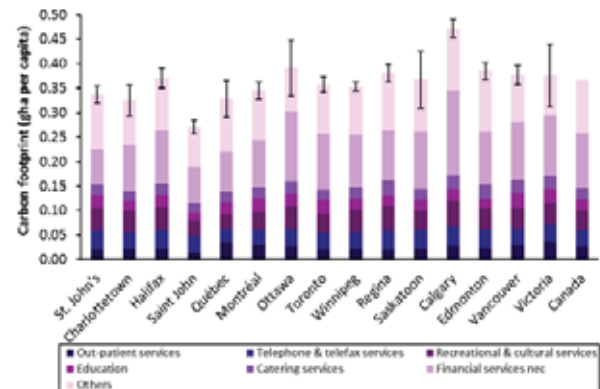


Figure 4: Carbon footprint from services

The good consumption is composed of 15 subcategories. Figure 5 shows the total CF for the total good consumption (CMU average for 6 years: $0.34 \pm 0.06 \text{ gha}$) and highlights the contribution of most important categories. The total CF from the good consumption category varies from 0.23 gha per capita in Ottawa to 0.42 in St John's. Clothing has a dominant impact on CF and represents 26% of the CF in Halifax, while it represents 44% of the CF in Ottawa. Most clothes are imported from abroad. Citizens of Victoria and Ottawa did not significantly report tobacco consumption and they are the two cities with lower CF. The tobacco footprint in Halifax appears too high and it must be checked later with other data sources. When comparing the two cities located on islands, St. John's and Victoria, Victoria has a carbon footprint a quarter lower than the most eastern city. Urban areas are known to have multiplication of consumption outside their budget and living environment [15].

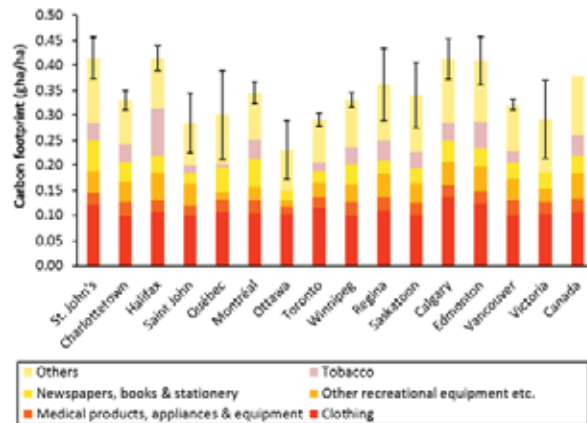


Figure 5: Carbon Footprint from good consumption

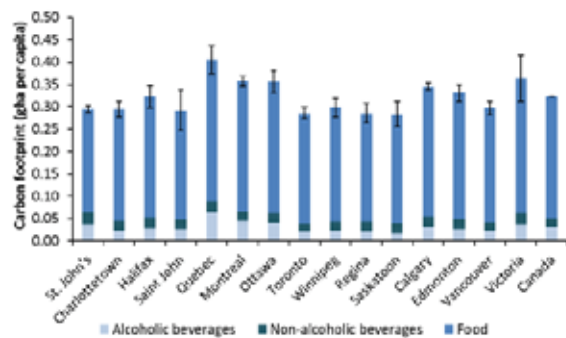


Figure 6: Carbon Footprint from food

The food category of carbon Footprint represents an average of 0.32 ± 0.04 gha per capita. It includes solid food, non-alcoholic beverages and alcoholic beverages with the former having the most significant impact of the three subcategories as it represents 81 to 88%. The other subcategories are low carbon Footprint indicator as they suggest 0.03 to 0.06 gha, as shown in Figure 6. In this study, the meat consumption was stable between cities, while it is an opportunity to reduce the food footprint [16, 17]. Inflation might not be completely taken into account in the scaling procedure and can affect the results. Higher food price can also be explained by higher food quality and not necessarily quantity, which is not taken into account in current calculation. The food component of the carbon footprint is relatively small, but when considering every component of the ecological footprint, food has more impacts [7]. A more detailed CLUM of the food component would also allow differentiating better the cities.

4. Conclusions and Outlook

This study highlight that the choice of electricity for housing in a city has a dominant impact on the carbon footprint of the cities. Transportation is the next categories having a large impact on the Carbon Footprint per capita. Cities with a higher proportion of

transport services than personal transportation has a lower carbon footprint. Technological advances in the transportation sector along to policies are needed to reduce the carbon footprint in Canada. The Carbon Footprint associated with the consumption of goods, services and food consumption has a lower impact. The methodology can be improved by taking into account uncertainty in yearly estimates and a more detailed CLUM of the food consumption. The scaling procedure can be further revised to take into account variation in the energy mix visible in the energy expenditures. Sustainability cities should aim to encourage citizens to reduce further their carbon impact, while still enjoying a good quality of life and reaching sustainable development goals.

Acknowledgements

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Thermal comfort monitoring in buildings using a BIM-based automated system

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Abstract:

A comfortable thermal indoor environment is crucial for employees' well-being and productivity. To reduce office ergonomics hazards from the thermal comfort level, this research presents a newly developed integrated solution based on a building information modeling (BIM) which provides significant improvement to ease of monitoring a building. An wireless sensor network (WSN)-based approach is used here to measure air temperature and humidity at a space within an office building, to monitor the thermal and humidity conditions. The data, measured by sensors, are sent via the wireless network to a remote database. An integrated workflow is developed to link between the database and a BIM-based model to visualize the temperature and humidity levels in an office environment. A case study is presented here in order to show the capabilities of the system developed. The system is able to detect time and location of the office room experiencing thermal discomfort based on targeted thresholds and trigger, and transmit alarms to building supervisors and facility managers via their wireless devices in near real time. The proposed solution is expected to facilitate intelligent monitoring of office spaces through near real-time integration of sensor data to BIM to maintain the level of thermal comfort at a satisfactory level, and at a much lower cost than traditional Building Management Systems (BMS).

Keywords:

BIM; BMS; Wireless sensor network; Building management system; Thermal comfort level.

1. Introduction

One of the issues in building's operational phase is thermal comfort of the occupants. When an office environment gets too warm, it makes employees feel tired. On the other hand, if an office environment gets too cold, it causes the employees' attention to drift, making them restless and easily distracted. Charles et al. [1] argued that indoor air quality (IAQ) and thermal comfort are the most important factors contributing to worker productivity, satisfaction, and well-being. According to the Canadian Centre for Occupational Health and Safety (CCOHS) [2], thermal comfort is met when a person wearing a reasonable amount of clothing feels neither too cold nor too warm.

It is essential to ensure that different thermal comfort conditions are within acceptable limits. Different factors influence the thermal comfort level of office environments, including temperature, metabolic rate, clothing, air speed (velocity), and humidity [2]. According to Health and Safety Executive (HSE) [3], the most commonly used indicator of thermal comfort is air temperature. However, temperature should be considered in relation to other environmental factors. Kumar (2006) [4] suggested that comfort can be achieved only when the air temperature and humidity

are within the specified range, often referred to as the 'comfort zone'. The CCOHS [2] suggested that the humidity levels should be kept between 30% and 70%. Relative humidity levels below 30% can cause discomfort through drying of the eyes and skin, while relative humidity levels above 70% may make the area feel stuffy.

In order to have an accurate record of existing environmental conditions throughout a building, temperature and RH must be measured and recorded with instruments designed for that purpose [5]. Computerized Building Management Systems (BMS) are usually used to monitor climate conditions and manage HVAC system. BMS is a customized system applied to large buildings or groups of buildings. BMS can also be used to provide temperature and relative humidity data for analysis [5]. Analogue and digital input signals tell the BMS what temperature, humidity, etc., is.

BMS deployment usually involves the installation of sensors, software, a network, and a cloud-based data storage, mostly applied to decrease the energy use, save money and maintain a good climate condition for the occupants. Unfortunately, BMS is traditionally expensive, complicated, and requires specific installation, programming, and maintenance. The average cost to deploy a basic BMS is at

minimum \$2.50 per square foot and can be as high as \$7.00 per square foot, equivalent to a minimum \$250,000 for a 100,000-square-foot building [6]. But most buildings are categorized as low-rise or mid-rise building. On the other hand, most of the modular buildings are low-rise buildings. For instance, high-rise buildings make up only 10 percent of the US commercial real estate stock, and 90 percent of the total building stock in the US and might *not benefit* from a *smart technology installed and are* unmonitored or not managed at all for energy or operational savings [6]. Consequently, there is a need for cost-effective automated monitoring of temperature and humidity levels to maintain the thermal comfort in an acceptable level in low-rise and mid-rise buildings. Research has been conducted to assess the degrees of thermal comfort among occupants of buildings, using surveys and mathematical models [7, 8, and 9]. However, these studies do not visualize building and spaces that can lead to the inefficiency of monitoring systems. The main objective of this paper is to integrate Building Information Modelling (BIM), as an effective visualization tool, to a WSN system with aimed at near real-time monitoring of thermal comfort in office environments

2. Research Methodology

The system is expected to be able to detect time and location of the building space experiencing thermal discomfort based on targeted thresholds in compliance with ASHRAE and CSA standards and tolerable relative humidity ranges as recommended by the CCOHS.

The proposed method comprises three main components: WSN, relational database, and BIM. Each of these components is described in detail below.

WSN is a smart board associated with a microcontroller. The smart board is connected to temperature and humidity sensors for collecting the thermal comfort data in a specified time interval.

The second component is a relational database developed in MySQL environment to house and update the captured sensors data. The microcontroller is coded to send the sensors' measurements to an online MySQL database via Wi-Fi every two hours, including eight humidity data and eight temperature data along with their measurement time. Therefore, every two hours the MySQL tables are automatically updated based on the newly captured sensor data.

The third component is the BIM-based model of an office building. The BIM model is used as a central model to visualize and monitor the thermal comfort levels of rooms remotely. Every two hours, when the MySQL tables are automatically updated based on

the new sensor data, the BIM model is also updated. To link between MySQL database (physical sensors data) and the BIM model (virtual sensors), thirteen modules were developed and coded in programming environment called, Dynamo, to automatically read temperature and humidity values stored in the database, sort the data, update the BIM model with latest real-time sensor data. Fig. 1 illustrates a schematic diagram that shows the data flow in the proposed model.

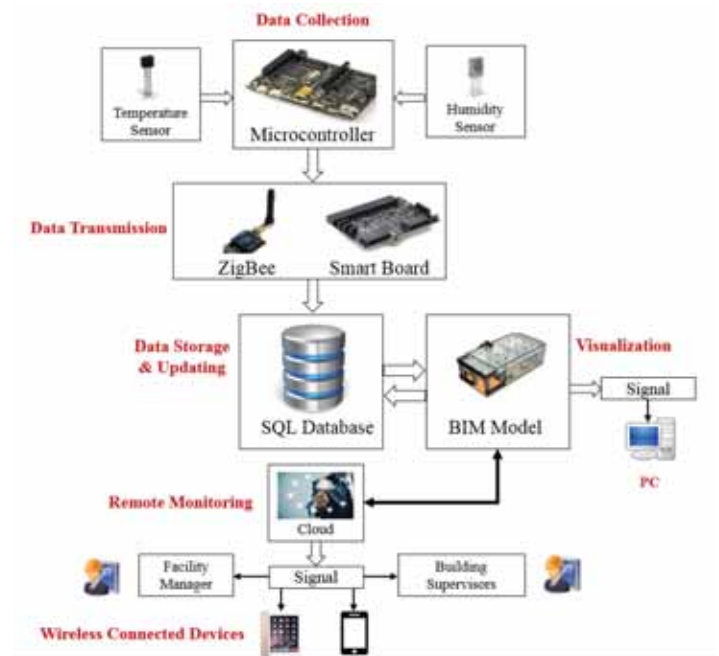


Fig. 1. Data flow in the proposed BIM-WSN integrated system

Fig.2 shows the hardware configuration system used in this study. As shown, it consists of a humidity sensor, temperature sensor, battery, microcontroller, smart board, and ZigBee wireless.

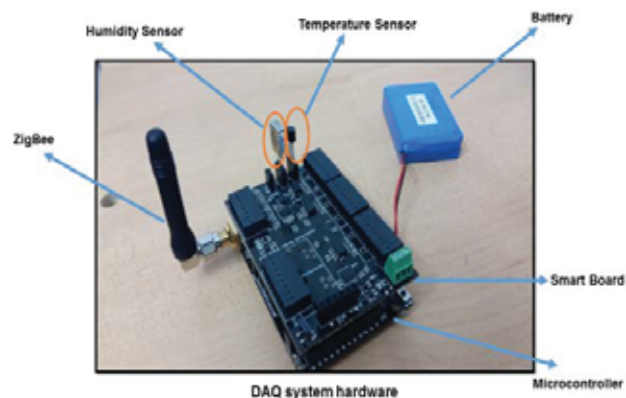


Fig. 2. DAQ system hardware used in this research

3. BIM Model

To demonstrate the capability of the proposed system, a two-story office building located in Ville Saint Laurent, Quebec, Canada was modeled in Autodesk Revit Architecture 2017 in this study as shown in Fig. 3.



Fig. 3. The BIM model

A set of parameters were introduced in the modeling process: 'LatestDateTime', 'Sensor_ID', 'Humidity', and 'Temperature' for the sensor objects; and 'Latest DateTime', 'Humidity Level', 'Temperature Level', and 'Thermal Comfort Check'. Two parameters, 'Humidity' and 'Temperature', were created to accommodate the maximum humidity and temperature values recorded by the humidity and temperature sensors at two-hour intervals. The 'LatestDateTime' parameter was created to accommodate the date and time of the maximum operative temperature measurement and the 'Sensor_ID' parameter was used to link the physical sensors to virtual sensors in the BIM model.

In fact, it is the physical sensors' specific ID that must be assigned to each corresponding virtual sensor in the BIM model to link the two types of sensors. 'Humidity Level' and 'Temperature Level' parameters were created for the 'Room' object to accommodate the latest 'Humidity' and 'Temperature' parameters values of the correlating virtual sensors in the BIM model, and the 'Thermal Comfort Check' parameter was used to monitor the working range condition of the instrumented room.

4. System Implementation

The modules described in the previous section were developed to introduce a workflow to link virtual and physical humidity and temperature sensor, update the associated parameters of 'Humidity Level', 'Temperature Level', 'Latest DateTime', and 'Thermal Comfort Check', and then highlight the corresponding office room in the BIM model based on its thermal comfort status at each time interval (eight readings).

The Waspmote-based DAQ system was coded to transfer the sensed temperature and humidity data to MySQL database server at each time interval. A query

was used in MySQL server to update the predefined tables and parameters at each time interval. Only two time intervals were used in this study to validate the proposed framework. Fig. 4 shows a sample of temperature values measured in the first and second time interval respectively, which were stored in their corresponding tables in MySQL server.

Record_ID	Sensor_ID	Sensor_Value	Recorded_AT
1	TemperatureSensor_1	26.50	6/17/2017 10:37
2	TemperatureSensor_1	33.50	6/17/2017 10:53
3	TemperatureSensor_1	27.50	6/17/2017 11:07
4	TemperatureSensor_1	38.50	6/17/2017 11:23
5	TemperatureSensor_1	30.50	6/17/2017 11:37
6	TemperatureSensor_1	31.00	6/17/2017 11:52
7	TemperatureSensor_1	35.00	6/17/2017 12:07
8	TemperatureSensor_1	32.50	6/17/2017 12:22

Fig. 4. Transferring sensors reading remotely to the database

Once the sensors data was introduced to the database, the values were retrieved from the MySQL database and sorted automatically in the module described in Section 4.6. The 'Sensor_ID', 'Sensor_Value', and 'Recorded_AT' values were captured, read, and sorted for humidity and temperature sensors that were installed in the office room. The maximum humidity and temperature readings of sensor values were extracted after the values were sorted.

When the sensors values were read and sorted, the virtual sensors parameters in the BIM model are automatically updated. Consequently, the parameters defined for the office rooms in the BIM model ('Humidity Level', 'Temperature Level', and 'Thermal Comfort Check') are updated.

When the parameters for a room in question are updated, the room is highlighted based on the colors defined in Table 1. Fig. 5 shows a picture of the actual BIM-WSN system developed in this research.

Table 3: Classification of office rooms based on their thermal comfort level and colour

Thermal Comfort Check Parameter	Colour
Normal!	White
Too Hot!	Red
Too Cold!	Blue
Unacceptable Humidity Level	Yellow

As shown in Fig. 6, the working range condition of the instrumented office room in the BIM model is 'Too Hot!' in the second time interval. Therefore, the room was highlighted in red in the second-time interval. As observed, the maximum temperature value was measured 32.5 °C at 12:22 PM.

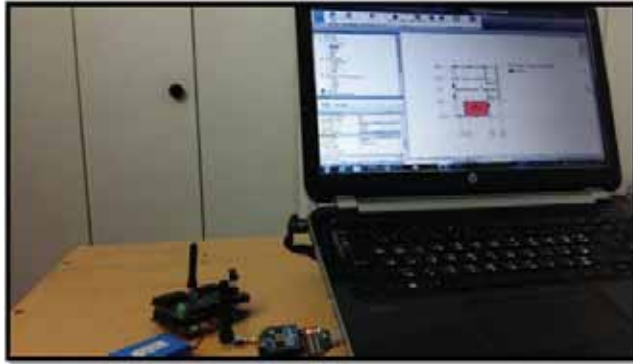


Fig. 5. Picture of thermal comfort monitoring test setup in the second-time interval

Data	
Latest DateTime	6/17/2017 12:22
Thermal Comfort Check	Too Hot!
Humidity Level	61.300000
Temperature Level	32.500000



Fig. 6. Screenshots of BIM user interface: second time interval

5. Conclusions and outlook

Monitoring of thermal comfort quality in office rooms is a critical task for building supervisors and facility managers. In this paper, a BIM-based framework for an automated thermal comfort level monitoring was developed and demonstrated. Based on the study presented here, the following conclusions are made.

- BIM's ability to assist in visualizing the monitored information helps building supervisors and facility managers to know the spaces experiencing thermal comfort problems and their locations.
- The integration of BIM and WSN through a specially designed database and a set of modules developed in Dynamo provides an effective visualization of office spaces associated with indoor air temperature and humidity levels.
- Storing the related data in a cloud provides the concerned authorities appropriate and timely access to the thermal comfort condition data of office rooms remotely through wireless connected

devices, leading to higher efficiency in monitoring office spaces.

- The system developed in this study was implemented, and its capabilities were illustrated through a case study. The system was able to detect time and location of the office room experiencing thermal discomfort based on targeted thresholds.
- The proposed system can be used in low-rise and mid-rise buildings where BMS is not usually used due to its initial high cost.

Acknowledgements

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The potential of natural superhydrophobic hollow milkweed fibers

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Abstract:

The valorization of abundant and renewable biomaterials with special properties from nature makes a great attention for both manufacturers and researchers. Milkweed fibres (Asclepiad fibre) are considered as perennial plants with umbel-like flowers, which are abundant in Nord American. Milkweed fibres are recently used for many domestic and industrial purposes such as isolating fabrics, water/oil separation membranes, ecological and non-animal winter garments. These fibres are very special because they have an ultralow density (5 times lighter than the jute fibre). However, there is a lack of information in the literature about the structure and morphology of this fibre, especially on the nanoscale level. In this present work, we will mainly a nanoscale IR (AFM-IR), a nanoscale thermal analyzer (nano-TA) and a high resolution FE-SEM to analyze the morphology and chemical composition at the nanoscale of milkweed fibres to provide a better understanding of its structure, especially on the surface. These results can contribute to identifying green applications in engineering.

Keywords: Nanoscale characterization, AFM-IR, milkweed fibres, superhydrophobic fibres

1. Introduction

The superhydrophobic materials bring a great attention for researchers due to its interesting applications fields such as self-cleaning¹, antiicing², antibacterial³, antifogging⁴, antifouling⁵, anticorrosion⁶, energy harvesting⁷, oil/water separation⁸. In the nature, lotus leave is considered as one of the most attractive natural superhydrophobic materials⁹ and becomes the symbol of outstanding hydrophobic material. Many bioinspired methods¹⁰ have recently developed to prepare superhydrophobic surfaces with a contact angle higher than 150° by the combination of double micro/nanoscale structures, following by the deposit of a water-repellent agent. Perfluorinated or silane compounds are often used for this purpose. However, their toxicity remains a big challenge for an eco-friendly and sustainable development. Here, we tried to use several advanced techniques likes AFM-IR to characterize the nanoscale structure and morphology of natural superhydrophobic hollow fibres. The finding and understanding in this work will shed light on the structure and nanoscale morphology of these abundant fibres and thus open promising new applications for green civil engineering.

2. Materials and Methods

Milkweed fibres are harvested from Granby, Quebec, Canada. The extraction of waxes-like is performed by using chloroform (Aldrich Sigma) at 80 °C for 30 minutes.

AFM-IR is carried on a nanoscale IR (Nano2S) as described in previous articles¹⁰⁻¹¹. A SEM (model

JEOL JSM-7400 F) was used to observe the exterior and interior fibre surface.

3. Results and discussions

This work provides an overview of the morphology structure and nanoscale structure of the Asclepiad fibres, the MEB images at different magnifications show that these fibres have a hollow structure

The preliminary results show that this fibre is homogeneously covered by secondary materials, which are expected to waxes or long chain alcohols. The molecular assembly of these waxes creates an island like the surface with the presence of a large number of nodules growing up and down on the whole surface. Interestingly, we also observed the same structure in the inner surface of the fibres and this will be an excellent property for the oil-like absorption (Figure 1).

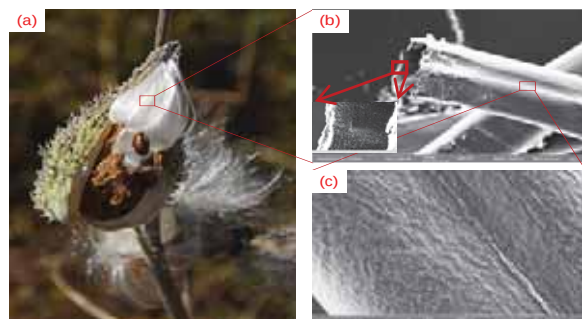


Figure 1: Asclepiad fibre: a) in the wild, b) observed by SEM showing the hollowed structure; c) high resolution SEM image, demonstrating the rough exterior surface, naturally covered by waxes. Insert image is showing the distribution of waxes at the interior surface.

The nanoscale IR spectra at the fibre surface show that there is a slight difference on the chemical composition between poor waxes region and rich wax region, especially on the concentration of carbonyl group (around 1700 cm^{-1}) and hydroxyl groups at about $1000\text{--}1200\text{ cm}^{-1}$ (Figure 2). This difference in IR absorption in the nanoscale need to further investigation by GC-MS and AFM-IR imaging to determinate the nature of waxes and their bonds with fibre surface.

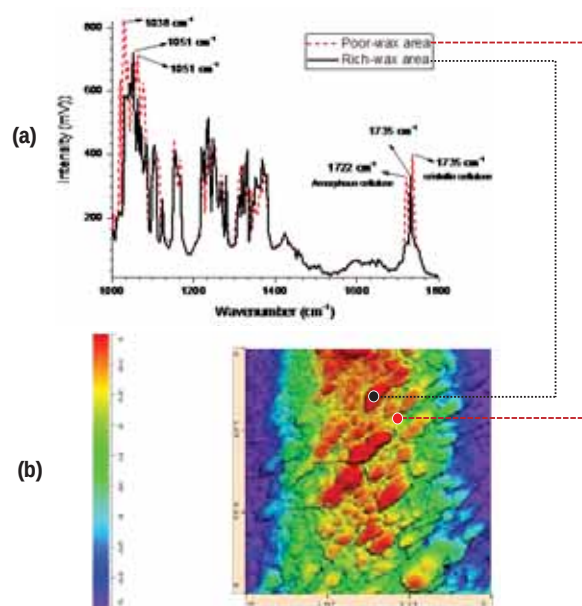


Figure 2: a) AFM-IR spectra of a milkweed fibre at the rich wax (black line) and poor wax (red line) areas; b) 3D AFM image of the fibre surface showing the spectral analyzed positions.

4. Conclusions and outlook

The characterization of this fibre is going on and a full understanding of the structure and morphology will be provided in next steps. Actually, preliminary results allow confirming several insights.

- 1) the wax likes are present on both sides of the fibre surface, not only on the exterior surface as expected,
- 2) the nanoscale IR spectra highlighted that the waxes like, contains not only long chain alkyl but also some functional groups. The nature of these compounds and theirs molecular assemble need to be further investigated by GS-MS and nano-TA, which will allow to better target green applications. Further characterization is ongoing to understand the potential new horizons of milkweed fibres.

5. Acknowledgements

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Principles of Load-Balanced Ground-Source Heat Exchange Systems for Optimization of Energy Efficiency in Building Heating and Cooling

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Abstract:

Ground-source heat exchange (GSHX) systems are an efficient option for coupling with building heating and cooling systems when applied under certain condition. By taking advantage of the thermal mass and heat capacity of the ground as a heat sink and heat source, relatively stable water temperatures can be provided to the source-side of a heat pump system, resulting in predictable and consistently high coefficient of performance. In an ideal scenario, a building's demand for heating and cooling would result in an approximately equal amount of total annual heat rejected to the GSX, compared to heat absorbed from the GSX. This balanced condition allows for smaller and more cost effective GSX size, for more stable and predictable seasonal ground temperature variations to be maintained from year-to-year, and for extended useful life of the system. However, due to variations in building type, occupancy patterns, and climate zone, most buildings' thermal energy demand profiles are typically heating or cooling dominant. Two case studies are presented to demonstrate how design and performance of a GSX are impacted by thermal load balancing. In the first example, a heating-dominant residential project is expected to absorb significantly more heat than it rejects; this continual imbalance of heat exchange will eventually result in GSX temperatures that are too cold for a heat pump system to operate effectively, without the use of supplementary boilers. In the second example, a cooling-dominant commercial office building is designed using a hybrid approach; the GSX is only used to the extent that heating and cooling energies are balanced on an annual basis, resulting in a smaller and more-cost effective GSX system that is expected to remain thermally stable over a very long term. The projections for both case studies demonstrate that the sizing, cost, and longevity of a GSX system varies significantly depending on application, even in relatively moderate climates.

Keywords:

Ground Source Heat Exchange, Ground Source Heat Pumps, Energy Profiles, Load Balancing, Optimization, HVAC, Heating, Cooling, Energy Efficiency.

Introduction

The building sector accounts for more than 20% of the world's energy consumption (US EIA, 2017), and of that, 60% of the energy consumption within the building sector goes towards space heating and cooling, and water heating (IEA, 2013); therefore, it is critical to continue to find and employ more energy efficient solutions to provide building heating and cooling.

In general, building heating and cooling systems involve the exchange of energy between the building's conditioned spaces, and a heat sink or source. A heat sink acts as a reservoir to accept heat rejected from the building during the cooling season; for example, a cooling tower treats the atmosphere as a heat sink, and excess rejected heat from a building is transferred to the air by way of convection and evaporation. Oppositely, a heat source provides the building with energy input during the heating season; for example, boilers convert chemical energy from a combustible fuel into thermal energy that is absorbed by the building.

Buildings with heat-pump based heating and cooling systems most often use the atmosphere as both a heat source and a heat sink. For example, a reversible air-source heat pump (ASHP) is capable of absorbing energy from the atmosphere for heating, and rejecting energy to the atmosphere for cooling.

The case studies presented in this article are provided for illustrative purposes only. Many factors influence the capacity and sizing of GSX systems, including climate, local soil conditions, and building energy use profiles. The figures presented in this article are approximate only, and are not intended to be used as a guideline for design of future projects.

Ground Source Heat Exchange (GSX) System

A Ground Source Heat Pump (GSHP) can use a Ground Source Heat Exchanger (GSX) as both a heat sink and source. Compared to using the atmosphere, a GSX interacting with high thermal mass of the ground provides more consistent temperatures over short periods and is not subject to wide or sudden temperature swings. However, the available heat capacity of a building-scale GSX is limited to the size of the GSX, whereas an air source system can consider the atmosphere as an energy sink with effectively infinite capacity.

For the purposes of this paper, only closed-loop GSX systems without significant thermal influence from groundwater movement are considered.

GSX systems should be distinguished from high temperature "geothermal" systems, where energy is extracted from deep within Earth's core in the form of hot water or steam. Geothermal is a form of renewable energy and its use is limited to areas with

active volcanic activity where the thermal energy of the ground is continuously recharged. GSHX, on the other hand, uses the ground as a means of storing low temperature heat, and is not considered a source of unlimited heat energy.

Components of GSHP System

A GSHP system consists four main components: 1) ground heat exchanger loops (the GSHX), 2) a buffer tank and/or header (this is optional, but recommended), 3) circulation pumps, and 4) a heat pump (Fig. 1). The two most common configurations of ground loops are vertical boreholes and horizontal coils. A horizontal coil configuration is typically used for smaller buildings with smaller loads, since the loop is not required to be exposed to a large volume of the earth. A vertical borehole field is more common for large commercial and institutional-scale applications, allowing greater loop lengths and surface area of piping, and thus greater exposure to a larger volume of the ground. The vertical ground loop is most commonly constructed of cross-linked polyethylene (PEX) or high-density polyethylene (HDPE) tubing, with thermally conductive grout to maximize the surface area contact and heat exchange with the surrounding soil. For a larger system, a buffer tank and/or header piping is recommended to provide a hydraulic break between pumping systems serving the GSHX and the GSHP. The GSHP may be either water-to-water (e.g. central heating/cooling plant) or water-to-air (e.g. terminal units within individual zones or suites). In both cases, the heat pump's vapour-compression refrigeration cycle is required to transfer energy against a temperature gradient, i.e. from "lukewarm" GSHP loop water to a "warm" heated space.

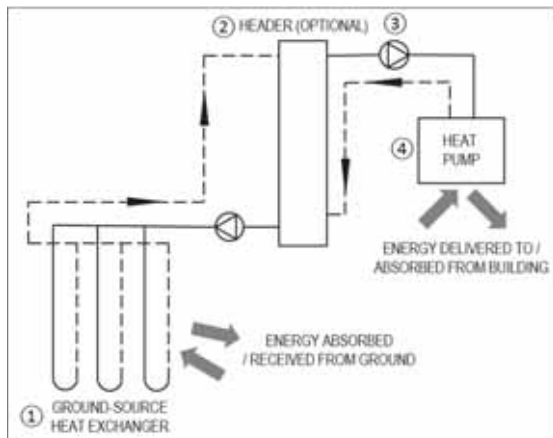


Figure 1. Components of a typical GSHX system : 1) ground loop, 2) optional header piping, 3) circulation pumps, and 4) compressor or heat pump.

Energy Efficiency of GSHX HVAC Applications

There are many benefits of using a GSHX system for building heating and cooling. One of the primary advantages is the potential for greater heat pump operating efficiencies.

Heat pumps use a vapour-compression refrigeration cycle to move energy from a lower to higher temperature. For example in a GSHX, a heat pump may operate to move or "lift" heat from "lukewarm" water circulated through the ground (perhaps 8°C), into "hot" supply air (perhaps 32°C).

Moving energy across a narrow difference in temperatures (smaller "lift") requires less input work by a compressor, and it thus operates more efficiently. Oppositely, moving energy across a wide difference in temperatures (higher "lift") requires more input work by the compressor, therefore the heat pump operates less efficiently. From an energy efficiency perspective, it's therefore advantageous to couple a heat pump with a heat source that maintains a temperature as close as possible to the heating temperature the building system requires.

GSHX systems take advantage of relatively stable temperatures of the ground, which can change gradually with time but are not subject to wide extremes, nor sudden changes due to weather or climate events. Annual average GSHP efficiencies are typically greater than for comparable air-source heat pump systems.

However, GSHX systems present unique challenges. The capital costs and time associated with excavation, borehole drilling, dewatering, freeze protection of such systems are often barriers to their more widespread use in commercial-scale applications.

A common misconception of GSHX systems is that they can be applied as an unlimited source of thermal energy at a constant temperature. The energy available from a GSHX is based on the thermal heat capacity of the ground/ earth volume interaction with the GSHX. Continual heat extraction can result in degradation of ground temperature over time.

A second important misconception of GSHX is that proper system sizing should be based on peak heating and/or cooling demands from a building (a maximum instantaneous rate), rather than total energy absorption/rejection (an annual total amount). While conventional heating and cooling systems (e.g. boiler/chiller) are often sized based on their ability to satisfy a peak "worst case" demand, a GSHX may be thought of as a dynamic thermal battery, where capacity is dictated by rate of discharge and subsequent re-charge.

Sizing of GSHX systems based on peak demand therefore results in relatively large field sizes, since this is analogous to selecting a battery for long-term

use that will never be recharged at the same rate that it is discharged.

A recommended approach for sizing of GSHX systems involves identifying the amount of heat extraction/rejection that can ideally be balanced on an annual basis. By selecting a GSHX size based on a balanced portion of a building's annual load (energy), rather than an instantaneous peak demand (rate), the energy efficiency benefits of a GSHP can be realized with lower total construction costs related to the GSHX.

Strategies for GSHX Load Balancing

Despite the unbalanced heating and cooling demands of most buildings, one strategy for achieving energy efficient and cost-effective energy-balanced GSHX systems is by supplementing a system with external heat sources or sinks. This allows the GSHX to be designed so that it is not the sole heat sink/source for a project. With supplementary heating or cooling, the GSHX size can be reduced by 30-40% compared to a GSHX sized to serve the entire heating/cooling load. The GSHX can also be optimized to only be used under conditions that will result in a thermally-balanced field, or to only be operated during more extreme ambient conditions, hence reducing the rate of ground temperature degradation.

Following are two case studies with distinct heating and cooling demand profiles, employing different strategies to determine an optimized GSHX system size. Both projects are located in Victoria, British Columbia, and utilize both heating and cooling (air-conditioning). Although the terminal system types are different, both projects use GSHX to satisfy a portion of their overall heating and cooling demands.

The average undisturbed ground temperature in Victoria is 10-15°C and with reference to ASHRAE and the BC Building Code's minimum requirements, design conditions are as follows:

- Winter outdoor temperature is -8°C (DB);
- Summer outdoor temperature is 28°C (DB) / 21°C (WB).

Case Study #1: Heating Dominant Residential

The first case study is a multi-building project that includes approximately 170 market residential units over three condominium blocks with approximately 15,000m² of conditioned space.

Similar to a typical GSHP system described in the previous section, this system consists of a closed-loop GSHX, a header, circulation pumps, a supplementary gas boiler plant, and terminal water-to-air heat pumps located in each residential unit (Fig. 2). This system utilizes a vertical loop configuration, with seventy-seven boreholes, each at 92m deep.

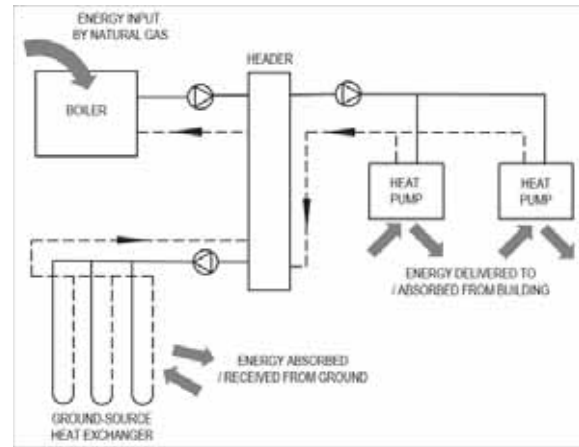


Figure 2. Case Study #1 System Schematic

An energy model was completed for this project to estimate total annual thermal loads of:

- 1,321,275 kWh/year heating
- 116,877 kWh/year cooling

The project is anticipated to be heating-dominant by a very significant margin, and would not be able to reject nearly as much heat into the ground during the summer, compared to the demand for heat absorption from the ground during the winter.

GSHX modeling software was used to project average ground temperature over a period of 50 years, with results indicating a steady decreasing trend (Fig. 3) due to the significant disparity between annual heating absorption and cooling heat rejection.

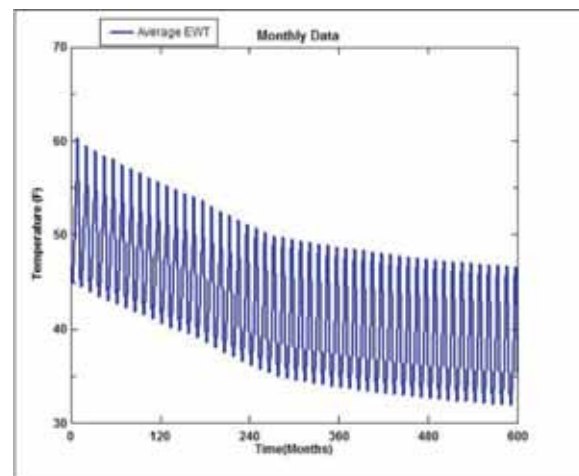


Figure 3. Monthly average entering water temperature from the ground loop over 50 years.

In light of the load imbalance, a gas boiler plant was implemented to provide supplementary heating, and decrease the reliance of the project on the GSHX as the sole source of heat absorption.

The modeling software was used to test, by iteration, the effect of long-term ground temperature based on what fraction of the total project's heating energy could be satisfied by the GSHX or by the supplementary gas boilers. These simulations showed that heavier reliance on the GSHX for heating resulted in a lower required boiler capacity, but a faster degradation of ground temperatures. Conversely, utilizing supplementary boilers more often resulted in slower degradation of the GSHX field, but consequently required a larger boiler capacity (and by association, greater consumption of fossil fuels and on-site emissions of CO₂).

Despite the gradual degradation of ground temperature over the simulated period of 50 years, this case study project will use dramatically less total energy, with lower GHG emissions, over 50 years compared to a conventional system using only boilers. As-designed, the project is expected to realize the benefits of the GSHX beyond a 50 year outlook.

Case Study #2: Cooling Dominant Commercial

The second case study is a commercial project consisting of 6-storey and 13-storey office towers, with approximately 26,800m² of conditioned space, sharing a hybrid air- and ground-source heat pump system.

Similar to Case Study #1, an energy model was completed to determine the following annual heating and cooling demand for the two buildings:

- 1,799,963 kWh/year heating
- 1,450,308 kWh/year cooling

In contrast to the first case study, the cooling demand for this project is only slightly greater than heating demand; the total annual energy figures are more closely matched between heating and cooling.

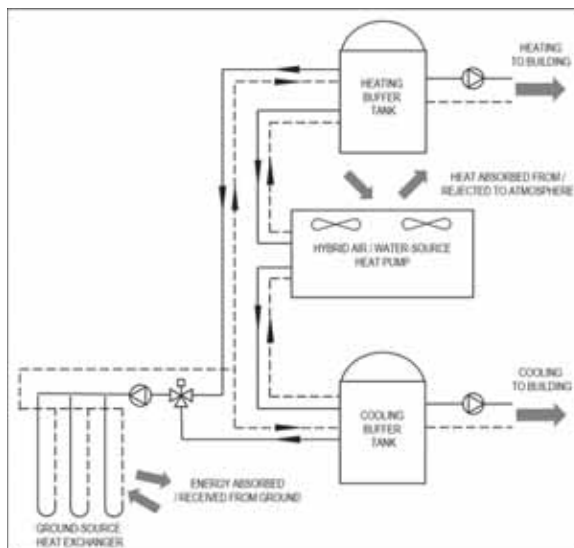


Figure 4. Case Study #2 System Schematic

This project employs a hybrid system that consists of a GSHX, heating and cooling buffer tanks, a hybrid air/water-source heat pump, and circulation pumps (Fig. 4). This system utilizes a vertical GSHX loop with ninety-three boreholes, each at 122m deep.

The ASHP satisfies the majority of the buildings' heating and cooling loads, while the GSHX is reserved for use during more extreme ambient air temperatures. That is, for the majority of the year when the ambient air temperature is in the optimal range for use as a heat sink/source (between 5°C and 18°C), the ASHP operates with a high efficiency. However, when the ambient air temperature is above 18°C during the cooling season, or drops below 5°C during the heating season, these ambient temperatures result in lower ASHP efficiency. In these circumstances, the hybrid heat pump plant changes to use the GSHX as a heat source/sink, since the ground can provide more stable temperatures during these select periods.

In this particular project, the hybrid heat pump system is also capable of internal heat recovery. Commercial and mixed-used buildings often require simultaneous heating and cooling, and in such cases energy can be moved from the cooling-side of the load to the heating-side of the load, eliminating the requirement to use the air or ground as a heat sink/source.

As the GSHX is designed as a supplement the ASHP only to maximize the overall system efficiency, it is prudent to ensure the field temperature stays within a selected design temperature range to prevent long term degradation.

Based on a set maximum field temperature of 25°C and a minimum field temperature of 0°C, the total cooling and heating demand, as well as the percentage of heating/cooling demand met by the GSHX, an energy model was used to confirm two factors: (1) that the designed system was able to maintain the field temperature (expressed as GSHX fluid temperature) within the 0°C to 25°C throughout the first year (Fig. 5), and (2) that the field was projected to remain thermally balanced throughout a period of 20 years (Fig. 6).

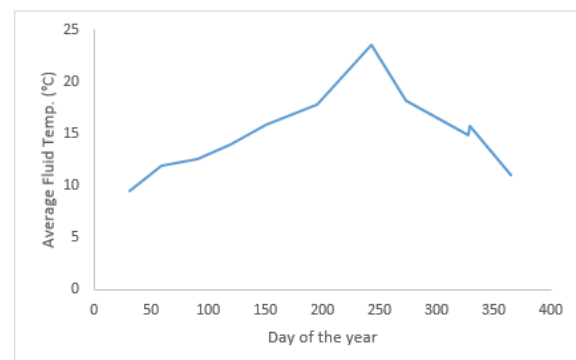


Figure 5. Average field temperature expressed as GSHX fluid temperature throughout the first year

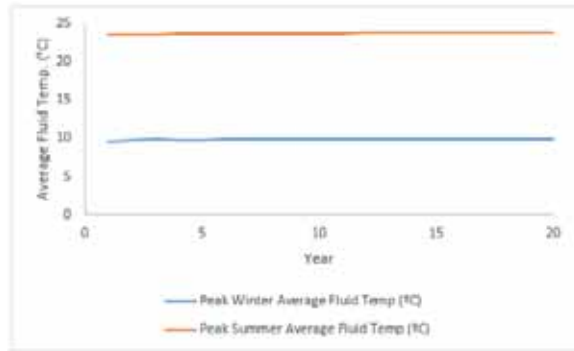


Figure 6. Peak winter and summer average field temperature expressed as GSHX fluid temperature over 20 year period.

Discussion and Conclusions

The case studies presented here illustrated examples of large projects where annual heating and cooling loads were not perfectly matched. Different strategies were employed to offset the result of disparity between annual heating and cooling energy, and reduce the effect of long-term change in GSHX water temperatures.

Projects with significant differences between annual heating and cooling requirements are generally recommended to first employ passive heating or cooling measures to reduce the dominant load and then use supplementary sources of heating or cooling, sized for the purposes of extending the expected useful service life of the GSHX, and maintaining the required size of the GSHX within practical and economical limitations.

Projects with less of a disparity between heating and cooling profiles can employ an approach where supplementary heating and cooling systems can be sized to operate only within a set of specific conditions. In the second case study, this resulted in smaller total equipment sizes, a reduced total GSHX footprint, and optimized heat pump efficiencies in both air-source and ground-source operation.

In both case studies, the GSHX was not sized based on satisfying the peak demand, nor on the entire annual energy associated with the building's heating or cooling needs. By maintaining the GSHX size to meet specific long-term relatively balanced annual heat extraction/rejection energy demand, and employing a hybrid approach to the system design, both projects were able to use smaller total equipment capacities, and maximizing the use of a smaller GSHX field.

Acknowledgements

We would like to acknowledge Miss Natalie Bragg (Integral Group), and Geotility Geothermal Systems for their support in the production of this article.

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Passive House Introduction Presentation

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Abstract:

The Passive House standard is internationally recognized for achieving energy efficiency and superior occupant comfort in new construction and existing buildings. The Passive House process includes spending considerable time during the design, detailing building systems that impact energy performance, and then testing, monitoring and confirming the design during the construction process. The Passive House standard has been referenced in Canadian codes, such as the Vancouver Building Bylaw, which allows Passive Houser Certified projects to undergo rezoning under an alternate rezoning path, and is under consideration in other jurisdictions across Canada. This presentation will provide attendees with an overview of the core Passive House principles and resources for additional information.

Keywords:

Passive house, thermal comfort, energy efficiency, energy model

1. Introduction

Climate change is the challenge of our generation. Growing evidence is driving international consensus for action to limit global warming below 2°C. Buildings consume up to 40 percent of global energy use and contribute up to 30 percent of annual global greenhouse gas emissions – they are a key piece of the puzzle towards a low-carbon future.

Passive House buildings consume up to 90 percent less heating and cooling energy than conventional buildings. Applicable to almost any building type or design, the Passive House high-performance building standard is the only internationally recognized, proven, science-based energy standard in construction. Certification ensures that designers and consultants are expertly qualified to design buildings to meet the standard.

The benefits of employing Passive House standards include fine-tuned control over indoor air quality and temperature with simple to use and durable systems, making them extremely quiet and comfortable throughout the changing seasons. The reductions in operating costs quickly make up any additional costs associated with construction, and the reduced carbon emissions provide priceless peace of mind.

Passive House is at the foundation of how we build better. It is how we feel better.

2. Format

With a one-hour time slot, the session will be a presentation format with time allocated at the end for discussion.

3. Content Overview

The presentation will be based on the content provided in the *110 Introduction to the Passive House Building Standard* course, offered by Passive House Canada, which provides an overview of the core Passive House design and construction principles.

The following key elements provided in this presentation will be covered.

Passive House Overview

We will begin with some context showing the prevalence of Passive House internationally and its current growth in the Canadian market at the local, provincial/ territorial and national code level

Passive House principles

An overview will be provided of the main principles of:

- Super-insulation
- Airtight construction
- Thermal bridge free design
- High quality windows, smart design
- Ventilation system heat recovery

Certification requirements, targets & recommendations

Certification criteria for the Passive House standard will be discussed, as they relate to the principles:

- Annual Space Heating/ Cooling Energy = 15 Wh/m².a (Either/Or with Heating Load)
- Heating/ Cooling Load = 10 W/m² (Either/Or with Annual Space Heating/ Cooling Energy)
- Airtightness = n₅₀ ≤ 0.6 /h, in both directions

- Summertime Comfort: Excess temp ($>25^{\circ}\text{C}$), frequency $< 10\%$
- Primary Energy (PER) ≤ 60 (PH Classic), ≤ 45 (PH Plus), ≤ 30 (PH Premium)

Depending on time limitations, we will also provide details around the recommended measures for achieving Passive House certification:

- Walls, Roofs, Floors = $U \leq 0.15 \text{ W/m}^2\text{K}$ (R_{IP}-40)
- Thermal bridge free = Ψ (Psi) $\leq 0.01 \text{ W/(mK)}$
- Windows = $U \leq 0.8 \text{ W/(m}^2\text{K)}$, SHGC ≥ 0.5
- Summertime Comfort: Excess temp ($>25^{\circ}\text{C}$), frequency $\leq 5\%$
- Ventilation with heat recovery efficiency $\geq 75\%$
- Ventilator electric efficiency $< 0.45 \text{ Wh/m}^3$

Examples

We will provide information from some local examples such as:

- Bernhardt Passive House, and
- North Park Passive House

presenting a simple economic study of these two projects, identifying factors such as the net monthly cost of ownership

Time permitting, we will review a list of other interesting projects currently operating or under construction worldwide.

Additional resources

Given the short timeframe, the focus will be on highlighting some of the key Passive House design principles and providing the attendees with available resources should they wish to learn more about the various aspects of Passive House design and construction. Resources will include additional classes, literature, and online links that are currently available,

Questions

We will allocate a few minutes at the end of the presentation for a question and answer period.

Acknowledgements

The authors would like to thank Passive House Canada for their support in delivering this workshop.

Passive House Energy Modeling Workshop

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Abstract:

The Passive House Planning Package (PHPP) is a complex spreadsheet-based energy model developed by the Passiv Haus Institut (PHI). It is the modeling tool used for the growing market of Passive House certification.

A pre-built, limited functionality Passive House Planning Package (PHPP) model of an existing home will be provided to participants. Participants will be provided with an overview of the project, the major concepts and aspects of the project that are the subject of the workshop, and some objectives/targets to try to achieve in the model.

The intent of the workshop is to provide a brief interactive example of how changes to various building envelope components affects total building energy use in a single-family home. The workshop will focus on the reduction of heating energy while staying within over-heating limits. The PHPP spreadsheet energy model will be mostly locked, with only select input parameters editable by participants.

Keywords:

Energy model, passive house, thermal bridging, PHPP

1. Introduction

Energy modeling is a growing field of work in both research and consulting, with much emphasis on leveraging these complex tools to achieve low energy building designs within budget constraints.

The Passive House Planning Package (PHPP) is simple compared to other purpose-built energy modeling software packages, and has been calibrated to real building energy use. It has been shown to have good accuracy, particularly for single family homes.

This workshop will provide participants with an opportunity to experience firsthand how an energy model can be used to inform design.

2. Walkthrough

The workshop will start with a brief overview of Passive House, followed by a walkthrough of the example project and the PHPP model provided.

Participants will be briefed on the design parameters available for edit, energy performance goals, and cost and thermal comfort limitations.

3. Workshop

Participants will be free to work in teams or individually in developing solutions to the given challenges.

The presenter(s) will be available to provide support and answer questions.

The project goals and compliance criteria may include:

1. Achieve PHI certification target(s)
 - o (Annual Heating ≤ 15 kWh/m²yr)
2. Stay within PHI overheating limits
3. Stay within budget
4. Achieve 1 through 3 for alternate climate

The model parameters available for edit may include:

1. Wall construction
2. Roof construction
3. Window specification (U-value and G-value)
4. Thermal bridging details
5. Site landscaping
6. Site shading
7. Site orientation

The PHPP models will be pre-loaded with multiple options for each of the above parameters, including costs for each. The model will compile costs for each solution automatically.

4. Results and discussions

After the participation portion, results will be collected from teams to see what solutions were achieved, and presented to the group. These will be compared with solutions the presenters had developed ahead of time.

The workshop will conclude with an informal discussion of the results, including comments and impressions from the participants.

5. Conclusions and outlook

The energy consumption of new and existing buildings is recognized to be an important area of focus as we move to reducing our footprint on the planet. Passive House is an internationally recognized standard for achieving low-energy building performance.

Energy modeling is a growing specialization that spans multiple design and engineering disciplines. This workshop will provide participants with a hands-on example of how energy modeling can be applied to real life projects to achieve design goals within project constraints and provide better general understanding of how the design of a building relates to its energy performance.

Acknowledgements

The authors would like to thank Passive House Canada for their support in delivering this workshop.

Passive House - Leading the Shift to High Performance Buildings

G. Verhulst, Architect AIBC, MRAIC, Certified Passive House Designer
Principal, Waymark Architecture

Abstract:

There is a rapidly increasing uptake of the Passive House standard in British Columbia today as its many benefits are being recognized by building owners and policy makers alike. As such, there is a need for building capacity within the construction industry to consistently deliver to this standard. This paper will outline the lessons learned from some local projects where the standard is either being sought or being considered.

Keywords:

Passive House, High-Performance Building, Energy Efficiency, Integrated Project Delivery, Collaboration, ...

1. Introduction

The Passive House standard has clear benefits for thermal comfort, indoor air quality, and reduced operating costs, which are benefits important to most building owners. The reduced energy demands, and the associated reduction in GHG emissions, makes the standards attractive to policy makers. These benefits are being recognized more widely, and in combination they mean an increasing demand for buildings to meet this standard.

Designing and constructing a building to the Passive House standard requires important changes to standard practices at most phases of design and construction. Owners, architects, engineers, general contractors, trades contractors, and material suppliers must all be involved in this change for a project to be successful.

While in the future high-performance is likely to be common practice, at this early stage of adoption leadership and teamwork is required to achieve the standard.

The design team, including architects and engineers, have a crucial role to play, and their leadership will have a pivotal role in the construction industry's ability to adopt high-performance building practices.

2. Format

With a one-hour time slot, the session will be a panel discussion format with time allocated at the end for questions and discussion. Panel will include myself, and engineer, and a contractor,

who have worked on at least one high-performance project together.

3. Content Overview

The presentation will be organized according to the topics listed below. On each topic, real world examples from projects currently underway or recently completed will be used to illustrate the points being made.

The Importance of Beginning with the Passive House Standard in Mind

Right from day one in a design process, decisions are made that will either make achieving Passive House certification straightforward and affordable, or difficult and expensive.

Considerations at Each Stage

An overview will be provided of the considerations that are important at each stage of the design, summarized here:

- pre-design: project delivery method and approach to integrated project delivery
- schematic design: shape, size, orientation; uses and associated internal heat gains; the location of the thermal envelope; heating and ventilation strategy; structural systems and their implications for thermal bridging and continuity of the airtight layer; and preliminary energy modelling.
- design development: envelope assemblies; major thermal bridge modelling; preliminary sizing of heating/cooling/ventilation equipment;

- treated floor area; detailed assessment of heat gains; and more detailed energy modelling.
- construction documents: continuity of airtight layer at all details; final sizing of mechanical equipment; modelling of all thermal bridges; and final energy modelling
- tendering / construction contract negotiation: how early in the design to involve a GC and/or major trades; special qualifications; avoiding “fear factor” pricing;
- construction: orienting workers on site; maintaining the airtight layer; sequencing the airtightness tests; quality assurance;

- Calder Residence
- SD 61 Modular Classrooms

Questions / Discussion

Ten to fifteen minutes will be allocated at the end of the presentation for a question and answer period.

Design and Teamwork

It is common that in a design process the work of different disciplines are siloed. This approach in a Passive House building risks cost and schedule overruns, or failure to meet the standard.

The experience working on recent local projects trying to be more integrated and collaborative will be discussed.

Communicating with Building Owners

It can be the case that a building owner takes a leadership role in pursuing the Passive House standard, and when that's the case the consultant team may just need to focus on achieving technical requirements.

If a building owner is reluctant or getting “cold feet,” the leadership of the consultant team is crucial to communicating the benefits of each departure from conventional practice that is necessary to achieving high-performance.

Discussion of local examples.

Communicating with Contractors

The GC and certain major trades must have “buy in.” Again, the leadership of the consultant team may play a pivotal role in whether or not the Passive House standard is achieved.

Recommending practices on-site and/or specifying them.

Discussion of local examples.

Examples

Throughout the presentation we will explore how the topic in question relates to some local examples, including some projects that are not to the Passive House standard, but could have been, including:

- Charter Telecom Headquarters

About the Editor



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Phalguni is an applied engineering researcher and started his research career in 1997, immediately after finishing his doctoral studies from the University of Sheffield, UK. Initially, his research focused on new construction materials and structural strengthening techniques. Soon thereafter, during his 15+ years tenure at the National Research Council Canada (NRCC), he expanded his research horizon towards the heat-air-moisture responses of exterior building envelope materials and systems. Hence, in a true sense, he is a multidisciplinary building envelopes and structures researcher who brings together the fundamentals of Civil, Mechanical and Materials engineering to address pressing concerns of the construction industry and its stakeholders.