Effect of Aging on Water Absorption Coefficient of Commercial Grade Stucco

by

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Supervisory Committee

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Abstract

One of the main detrimental factors for the durability of exterior building envelopes is the presence of water. Capillary rise is a major mechanism for water penetration inside the building materials in the liquid state. It affects the energy efficiency and durability of buildings. Water absorption coefficient is used to characterise the capillary water intake into the porous building materials. Various research works have been done to describe the effect of surface water temperature on water absorption coefficient of different building materials. In this project, the effects of extreme temperature (hot: 60°C and cold: -10°C) aging on water absorption coefficient of stucco material is investigated. Six specimens are exposed at two temperature cycles (i.e. total twelve specimens) for fourteen days. Following the ASTM standard test procedure, water absorption coefficients of stucco samples are calculated and the effects of extreme weather aging are documented. These experimental values of water absorption coefficient are entered as inputs for hygrothermal performance analysis of stucco-clad wood-frame wall assembly. The experimental results show significant impact of extreme temperature on the water absorption coefficient of stucco materials and hygrothermal simulation outputs indicate that the change in water absorption characteristics of stucco due to extreme temperature aging can have measurable change in moisture management capacity of stucco-clad wood-frame wall assembly in Vancouver, BC.

Chapter - 1 Introduction

In North America, building envelopes are exposed to the extreme temperature fluctuation which varies in between of -30ºC to +60ºC. This temperature is one of the major driving force for moisture movement and it affects the moisture response properties of many building materials. This change in moisture response of building material due to extreme temperature exposure has a long term effect on the moisture management planning of the building envelopes. Increment in temperature results in greater mobility of water molecules present in any phase (vapour or liquid) inside the building materials. There are many research activities reported to date on this topic but the influence of temperature on moisture movement inside the building materials is not perfectly understood [1].

Building materials have small pores through which water penetrates in several ways. Karoglou et al. (2005) described various ways in which water can reach inside the building materials. This water mainly originates from driving rain, condensing of moist air, ground water capillary suction, water vapor transmission [2]. Building materials possess a specific amount of physically bound water without causing any performance issues. But if building materials contain moisture above certain percentage, it causes physical, chemical and biological issues [3].

1.1 Objective and contribution

All the research works done in the past for the water absorption coefficient of the various exterior building cladding materials were based on changing the water surface temperature [1,4]. While in real world situation, the outside layers of the building cladding, such as stucco, are exposed to various temperature regimes. Typically, in the North American countries this temperature range is anything between -30ºC to +60ºC.

Main objective of this project is to expose the stucco specimens to specific temperature cycles for specified period of time in controlled room. After treating the specimens at specific temperature cycles, water absorption coefficient of each specimen is obtained using standard test apparatus following the well-established ASTM testing procedure.

The difference in measured values of water absorption coefficient of the stucco, treated at various temperature regimes, can be related to the hygrothermal performance of the building envelope. To evaluate this effect of change in the water absorption coefficient of the stucco specimens, hygrothermal simulations are done using WUFI (Warme Und Feuchte Instationar) software. These simulations will demonstrate the effect of change in water absorption coefficient on the hygrothermal performance of the building envelope.

1.2 Report outline

The structure of the remaining sections of the report is as follows:

- Chapter 2 provides basic information about water absorption coefficient and some background on different research works done so far on water absorption coefficient of building materials.
- Chapter 3 represents the apparatus used for this project work and in detail experimental procedure.
- Chapter 4 represents the results obtained from the experimental work with the final graphs and tables for the water absorption coefficient.
- Chapter 5 concludes the report and discusses possible future work in this area.
- Chapter 6 lists all the references used for this project work.

Chapter - 2 Background

In various parts of North America, wood-frame walls with the stucco as exterior cladding are widely used. Due to the temperature conditions and rainfall all year round, specifically in British Columbia, these walls experiences moisture related problems. These moisture issues can lead to serious damage of the structure, which in turn cause serious performance issues and financial loses. One of the major causes of the moisture related issues in stucco cladded walls is capillary rise due to the rain fall and wet conditions. Researchers around the world have studied water absorption coefficient of different materials using standard test methods to determine water absorption coefficient [5].

2.1 Capillary rise

Capillary rise is the main mechanism which causes penetration of liquid water into building material. It can be defined as the upward vertical movement of liquid water through a permeable wall structure [6].

Water molecules driven by capillary force can rise through the porous structure of the building materials. This force is greater for small capillaries and it is inversely proportional to the pore radius as per the Jurin's law, which is governed by following equation [7]:

$$h = \frac{2\sigma cos\theta}{\rho g r}$$

where h = height of the vertical rise in capillary,

r = mean radius of the capillary pore,

σ = the surface tension of the liquid,

θ = the water contact angle,

ρ = the water density, and

g = the gravity acceleration.

Capillary water absorption method is widely used by researchers to obtain the liquid water absorption coefficient of building materials.

2.2 Water absorption coefficient

Capillary water absorption coefficient is one of the major properties of building material. It governs the liquid moisture movement into the building envelope. It is expressed as the rate of absorption of water due to the capillary force in the building materials [6]. Any material that allows liquid moisture diffusion through its boundary surface will change its weight with respect to time, given it is in contact with the liquid water as shown in the figure 1.

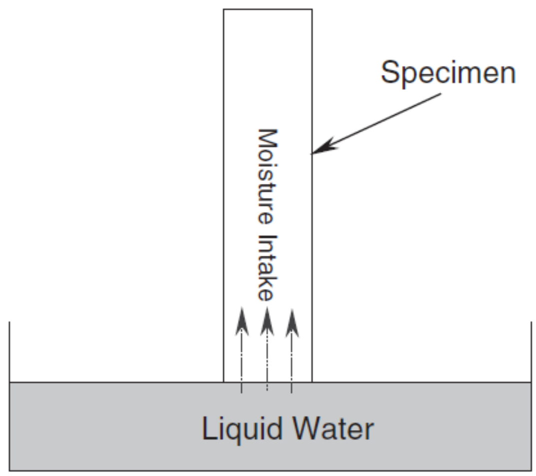

Figure 1: Moisture movement from surface contact with liquid water [8]

A schematic plot of the amount of water absorbed versus the square root of time is shown in the figure 2. The slope of this linear variation is known as the water absorption coefficient (A_w) and which can be mathematically written as [8]:

$$A_w = \left(\frac{Mt - Mi}{A\sqrt{T}}\right)$$

where

M_t = weight of the specimen after time ‘T’,

M_i = initial mass of the specimen,

A =liquid contact area of the specimen,

T =time.

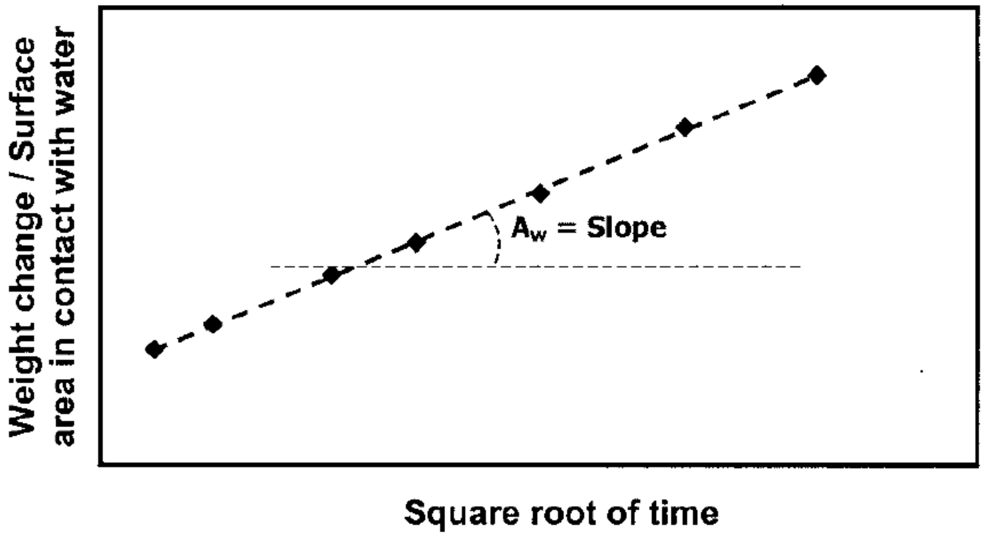

Figure 2: Results from water absorption test [8]

2.3 Research background

Many researchers have estimated the water absorption coefficients of various building materials. Several European and international standards are available as sources of information for estimation of water absorption coefficient.

In a paper published in 2002 [8], the authors determined the water absorption coefficients of three commonly used building materials (eastern white pine, red clay brick and concrete) at four different temperatures (3, 12, 21 and 35 ºC). During the tests, all specimens remained at the ambient room temperature of 23 ºC. The water surface temperature (in contact with specimens) was maintained at the specified temperature. Average water absorption Coefficient obtained from this experimental work is described in the table below [8].

Table 1: Water absorption coefficient of various building materials [8]

Material Type	Temperature Range			
	T1= 3ºC	T2= 12ºC	T3= 21ºC	T4= 35ºC
Eastern White	0.0075	0.0094	0.0112	0.0142
Red Clay Brick	0.068	0.066	0.084	0.065
Concrete	0.174	0.175	0.184	0.178

The results show linear increment in the water absorption coefficient of Eastern white pine. For Red clay brick the variation was uncertain. While for the Concrete, there was no significant difference in the water absorption coefficient with respect to the temperature increment.

In another paper published in 2002 [4], the authors tested total eight types of the base coat stucco specimens. Four of them were tested first to establish water vapour permeability and water absorption characteristics of the stucco material. In second phase of the work, stucco mixes were modified to obtain high performance stucco (i.e. Low water absorption coefficient and high water vapor permeability). The experimental results from this research work are summarized below [4].

Phase I: Commercial Stuccos

Table 2: Water absorption coefficient of base case stucco materials [4]

Stucco Type	Water absorption Coefficient ($Kg.m^{-2}. s^{-1/2}$)
Commercial Stucco I-N1	$0.0095 \pm 23.00 \times 10^{-5}$
Commercial Stucco II-N2	$0.0008 \pm 4.93.00 \times 10^{-5}$
Commercial Stucco III-N3	$0.0039 \pm 5.66 \times 10^{-5}$
NBC Stucco-N4	$0.0235 \pm 54.00 \times 10^{-5}$

Phase II: Modified Stuccos

Table 3: Water absorption coefficient of modified stucco materials [4]

Stucco Type	Water absorption Coefficient ($Kg.m^{-2}. s^{-1/2}$)
Hydrophobic coating on exterior surface-M1	$0.0016 \pm 6.98.00 \times 10^{-5}$
Hydrophobic aggregate-M2	$0.0130 \pm 38.90 \times 10^{-5}$
Aggregates coated with hydrophobic chemical-M3	$0.0013 \pm 7.09 \times 10^{-5}$
Zinc stearate as admixture-M4	$0.0010 \pm 4.81 \times 10^{-5}$

This study showed possible improvement in the water absorption coefficient of stucco by adding appropriate hydrophobic aggregates.

In a paper published in 2016 [6], the authors compared three European test standards [EN 1925, UNI 10859, normal 11/85] illustrating 3 different methods (one tangent, two tangent, 30 min method). Authors compared these methods to identify the most appropriate method for calculating water absorption coefficient. In this research work, 3 materials (stones, bricks, mortar) at 3 different temperatures (20, 25, 30º) were tested [6].

Another research work was published in which the authors illustrated experimental set up for automated water uptake test. This setup determined the water absorption coefficient as per EN ISO 15148 [9].

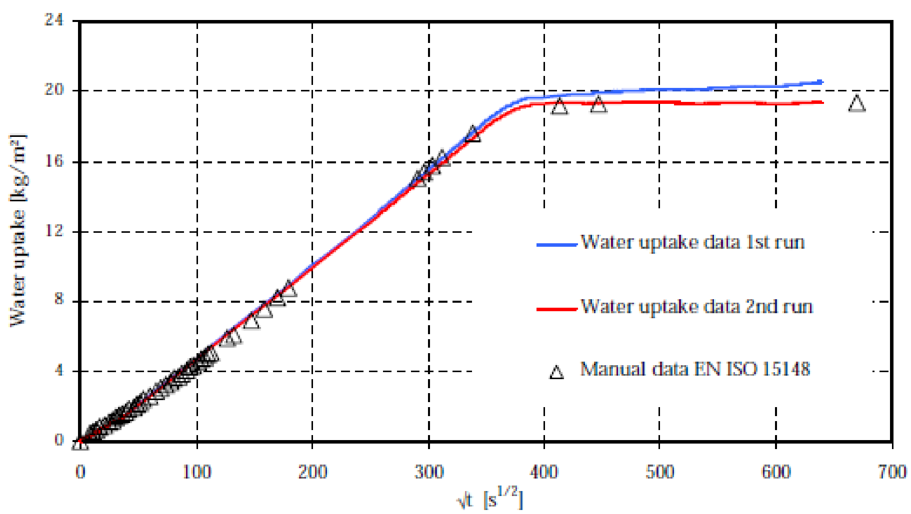

Figure 3: Automatic water uptake experimental data [9]

A paper published in 2014 [2], explained the physical, chemical and biological effects due to higher moisture content inside building materials. It also explained some of the main decaying mechanisms [2]. In a paper published in 2002[10], the authors tested effect of karlocolor external paints (applied as coatings) on the glass fiber reinforced concrete. Coatings were found effective water protective materials in short term water exposure of up to 10 hours. The paint layers decreased cumulative water mass content in specimens more than four times, compared to specimens without paint [10].

In a research work published in 2005[11], the authors did an experimental study on application of time domain refectory (TDR) method. Moisture profiles of building materials were generated using TDR method. This method does not require calibration of each specimen. This study showed that TDR is highly suitable for the materials with higher salinity, where common methods are not applicable due to loss of accuracy [11]. In a research work published in 2015[12], the authors studied the effect of temperature on water absorption coefficient of brick. Specimens were tested within temperature range of 5ºC to -55ºC at controlled conditions. Two types of numerical simulations were performed, results of both showed quite similar output. Which proves that WUFI allows a sufficiently accurate description of the wetting phenomenon [12].

In a research work published in 2018[13], Concrete specimens with paraffin wax were tested. Conventional concrete specimens have high water absorption coefficient and low resistance to water penetration. Therefore, the authors studied modified concrete specimens for the water absorption coefficient. Specimen type 1: Portland cement, paraffin wax and a 0.40 water-to-cement (w/c) ratio by weight (without addition of paraffin wax). Modified specimens with the addition of 10 %, 20 %, 30 % and 40 % of paraffin wax by weight of the cement. Concrete specimens with 20% paraffin wax addition have a water absorption coefficient less than 0.007 (kg. $s^{-1/2}$ m^{-2}). They are classified as a hydrophobic material. Future research can be carried out for the durability and variation of the compressive strength by addition of the paraffin wax [13].

Most of the research work done on water absorption coefficient of building materials were based on changing the surface water temperature (which is in contact with the bottom surface of the specimens). While in real world situation, building materials are exposed to various temperature and environmental conditions. These all parameters can make significant difference in water absorption coefficient of the outside building claddings over the time.

2.3 Estimation of water absorption coefficient as per ASTM C1794-15[14]

To obtain the water absorption coefficient of specimens, standard guidelines provided in ASTM C1794-15 were followed, which is described briefly below:

The main purpose of this test procedure is to obtain reliable data on the capillary water uptake of building materials using a simple apparatus. The obtained data can be used as material properties for hygrothermal simulation of the building envelope for design and other research purposes.

2.3.1 Apparatus for the experimental work

The apparatus for the experimental work must contain the followings:

1. A scale to measure the weight of the specimen within accuracy of ±0.1% of its mass.
2. A water circulation tank with a reliable circulation system which can keep the water level constant within ±3 mm (1/8 in) and a setup to maintain the bottom surface of the specimen at least 5mm (1/4 in) above the bottom of the circulation tank.
3. An equipment to record the time with accuracy of minimum 1 second.

2.3.2 Procedure

1. All the procedures must be performed under the specified test conditions (table 4)

Table 4: Test conditions

	Temperature
Allowed range of test conditions	18 to 23ºC (64 to 73ºF)
Allowed variation during test	±2ºC (±4ºF)

2. Record the weight of all specimen at steady state with accuracy of ±0.1% of its mass which is to be recorded as m_i.
3. Fill the circulation bath with water up to the required level and wait till the temperature of water is same as that of the specimens.
4. Place the specimens in the circulation bath such as the bottom surface of the specimens are at least 5 mm above the bottom of the bath. Adjust the pin/clamp such as, bottom surface of specimen is 5mm (±2.5 mm) submerged into the water.
5. Major face of the specimen should be in contact with the water surface.
6. Start the stopwatch precisely when the specimen surface first comes in contact with the water.

7. After first 5 minutes, remove the specimen and press the wet surface against moist sponge to remove excess water drops. After that take the weight measurement of the specimen and return it to the original position. All this is should be done within 1 min of time to maintain accuracy. Repeat the same procedure and take at least two more readings within next 24 h to derive series of measurements for m_i at time t. Make sure to take a measurement at 4 h.
8. If liquid water shows up on top surface of the specimen, terminate the experiment.
9. In case the liquid uptake is less than 0.001 kg/m^2, material can be specified as resistant against liquid water uptake.

2.3.3 Calculation and results

1. Calculate area A of each specimen perpendicular to the surface which is in contact with water
2. Calculate the difference of area to the mass at each weighting as below equation:

$$\Delta mt = \frac{mt-mi}{A}$$

3. Plot the graph of Δmt against the square root of the time √t.
4. Obtain the water absorption coefficient using following equation:

$$Aw= (\frac{Mt-Mi}{A\sqrt{T}})$$

where

Mt = weight of the specimen after time ‘t’,

Mi = initial mass of the specimen,

A =liquid contact area of the specimen,

T =time.

2.4 Brief introduction of WUFI software

WUFI is derived from Warme Und Feuchte Instationar which means heat and moisture transiency. WUFI does realistic calculations of the 1-D and 2-D heat and moisture transport in walls as well as other multi-layer building envelopes [15]. This building envelopes can be exposed to natural weather cycles of North American region. [15]. WUFI provides a platform to design the wall envelope in simplified manner. Each layer of the wall design can be chosen from the available data set and also can be manually modified. Specific properties of the building materials can also be altered for various simulation purposes. Heat and moisture related studies over different weather conditions can be done using WUFI. WUFI uses practical weather data sets of different locations to simulate the expected hygrothermal performance of the wall envelope.

To analyzing effect of change in water absorption coefficient of stucco, WUFI Pro student version was used to run simple hygrothermal simulations. In detailed explanation of the wall design and parameters chosen for this simulations are described in the chapter 3.

Chapter 3 Experimental work

The ASTM standard C1794-15 test method is used to determine the water absorption coefficients of the stucco specimens.

3.1 Apparatus

Following Apparatus were used during the experimental work:

1. **Scale:** A measuring scale used for this research work was manufactured by Sartorius. Maximum weight that can be measured with this scale is 6100g. Readability of the scale is 0.01g which satisfies the requirement as per the ASTM standard C1794-15.

Figure 4: Sartorious weight scale

2. **Water circulation apparatus:** Water circulation tank with the submersible pump is used to create laminar water flow. This apparatus was designed by Mr. Matthew Walker as per the requirements of ASTM standard C1794-15. This apparatus is able to test 12 samples (of dimension 2” × 2”) at the same time. Clamps are provided for easy removal of the samples while taking the weight measurements. In the bottom part of the apparatus different levels of water are created by providing the partition. This stabilizes the water flow.

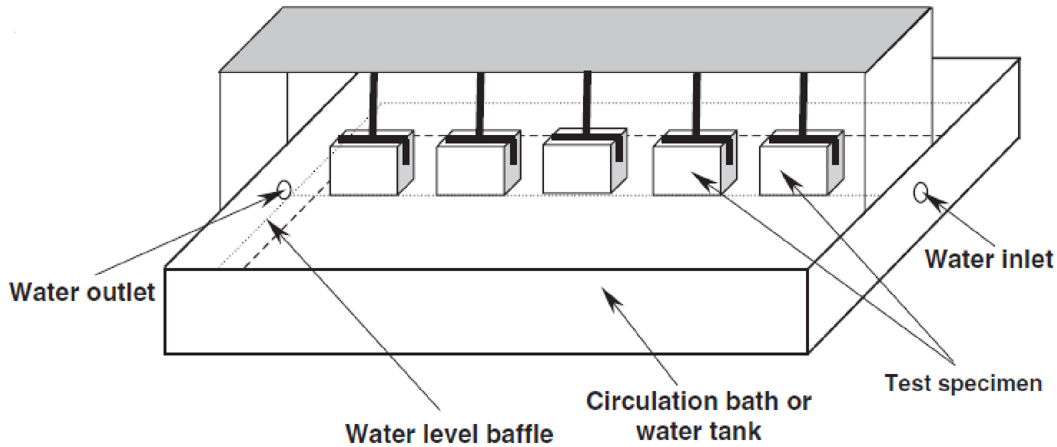

Figure 5: Schematic diagram of the circulation water tank[8]

3. **Stopwatch:** Stopwatch with accuracy of 1 second is needed for the procedure as per the ASTM standard. Cellular stopwatch was used during the experimental run which has accuracy of 100th part of second.

3.2 Experimental procedure

The experimental work for this research work was carried out in following phases.

1. Selection of the commercial grade stucco
2. Preparation of the samples
3. Coating of the samples
4. Testing the virgin samples to obtain its water absorption coefficient
5. Aging of the samples by keeping them in various temperature cycles

3.2.1 Selection of the commercial grade stucco

For the experimental work, QUIKRETE commercial grade stucco was selected. This material was bought from Slegg building materials in the bag of 80lbs (36.3 Kgs). This is a Portland cement based stucco. It is designed to be used as the scratch and/or brown coat in a 3-coat stucco application, or the first coat in a 2-coat application. This product contains special additives which prevent premature loss of water from the mix and provide increased workability.

3.2.2 Preparation of the specimens

Sample preparation was done in following phases

⇨ **Preparing the mix:** The mixture was prepared in small batches as per the guidelines provided by the commercial supplier. For creating 3kg of the stucco mix, 400ml of water was added in each batch to maintain the continuity. The mixture was than thoroughly mixed using the small batch mixture in the lab.

Figure 6: Small batch mixture

⇨ **Pouring into the molds:** The prepared mixture was poured into the molds as seen in the figure below. The molds were than tapped with the wooden hammer to make sure the mixture is properly spread in the mold. The excessive stucco mixture on top was removed by rolling the tamping rod over the mold.

Figure 7: Stucco moulds

- **Removal from the molds:** 48 hrs of settling time was allowed after pouring the mixture in molds. Stucco specimens were carefully removed by dismantling the mold. Removed specimens were inspected for any major defects. Once specimens were found in good shape, a coarse sand paper was used to remove the excessive edge laying out.
- **Curing:** According to the standard guideline provided by the commercial supplier, curing of the stucco specimens was started. For curing purpose, all the specimens were placed in a water bucket which was kept in controlled room (at the temperature 23ºC and Relative Humidity 50 %.) The molds were kelp in the water bucket for exactly 28 days.
- **Conditioning of the samples:** As per ASTM standard C1794-15, all the test specimens shall be stored under the test conditions (table 5) until the mass of each specimen has stabilized within 0.1 % of its total mass (when measured over 24h).

Table 5: Room condition

	Temperature
Allowed range of test conditions	18 to 23ºC (64 to 73ºF)
Allowed variation during test	±2ºC (±4ºF)

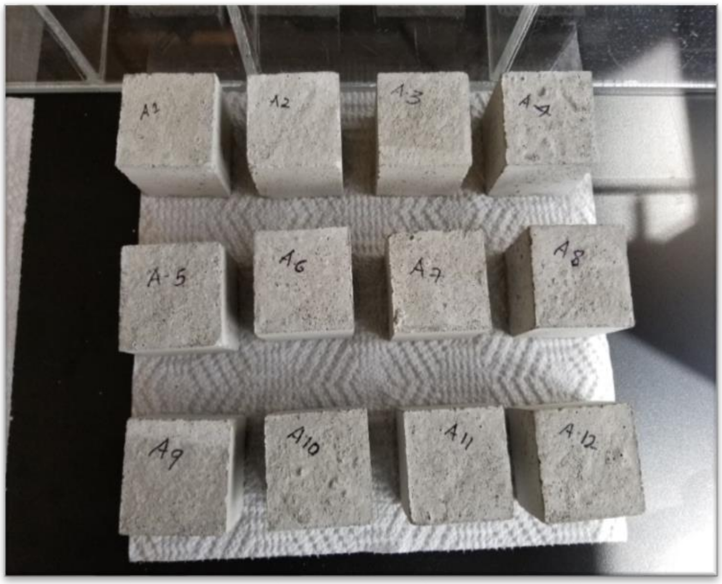

Figure 8: Conditioning of the specimens

Weight measurements over the 24 hours for the samples can be seen in Appendix.

- **Coating the samples:** After conditioning, the four side surfaces of the specimen was coated with the wax. Wax was used in mix of 60 to 40 % weight ratio of bees to gulf wax. This creates an impermeable vapor-tight sealant. The wax does not significantly penetrate into the pore of the stucco specimens.

3.2.3 Aging of the samples by keeping them in extreme temperature cycles The two sets of samples (six in each) were prepared for the specific study. One set of samples (A7 to A12) were kept at -10ºC in a cooler for 7 repetitive temperature cycles (i.e. for 24 h the samples were kept in cooler at -10ºC and for next 24h they were kept at the test conditions). This was repeated for 7 cycles in total. Another set of samples (B1 to B6) were kept at +60ºC temperature in oven for 7 repetitive temperature cycles (i.e. for 24 h the samples were kept in oven at +60ºC and for next 24h they were kept at the test conditions). This was repeated for 7 cycles in total. After the 7 cycles were completed for each set of specimens, following the standard ASTM C1794-15, water absorption coefficient of each set of specimens were obtained.

Table 6: Cold temperature cycle

	Temperature
Allowed range of Cold temperature	-10ºC (14ºF)
Allowed variation during test	±2ºC (±4ºF)

Figure 9: Samples inside the cooler

Table 7: Hot temperature cycle

	Temperature
Allowed range of Hot temperature	+60ºC (140ºF)
Allowed variation during test	±2ºC (±4ºF)

Figure 10: VWR oven used for exposing samples to hot temperature

3.2.4 Testing the virgin samples to obtain its water absorption coefficient

Specimens A1 to A6 were first tested, following the standard method described in ASTM C1794-15 to obtain the water absorption coefficient.

Figure 11: Testing the samples to obtain water absorption coefficient

- ⇨ All the specimens were firmly hold by the clamp as can be seen in the figure. Initial weight of the specimens (with the clamping holder) was recorded. The water tank was filled with the water and submersible pump was turned on to start the circulation of water. The temperature of the water was adjusted by adding hot/cold water until the desired temperature (18 to 23ºC) was achieved. The water level was allowed to stabilize before starting the experimental procedure. All the specimens were then kept above the water surface such that only the bottom surface of the specimen remains in the contact with the water surface. The water level was kept constant within the range of 5±2 mm above the bottom surface of specimen throughout the experimental run.

- Stopwatch was started as soon as the specimen surface was brought in contact with the water surface. At specific time interval the specimens were taken out from the water with the clamps. The wet surface of the specimen was pressed against multiple layers of the absorptive tissue papers. Each specimen with the clamp was then weighted carefully with the precision of 0.1% of its weight. All specimens were then returned to the water tank and weight measurement were taken periodically over next 24h

3.3 Wall design for 1-D WUFI simulation

Simple wall configuration used for WUFI simulations is shown in Figure 12. This type of wall is used in residential North American buildings.

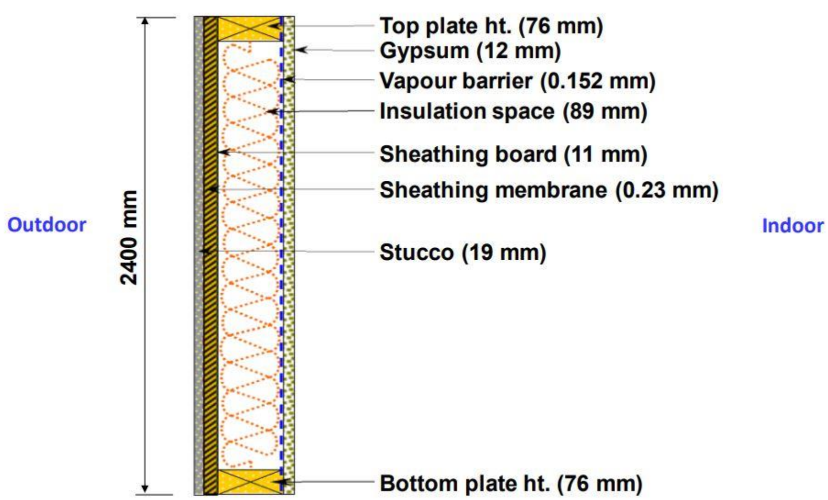

Figure 12: Stucco-clad wall assembly for WUFI simulation

Figure 13 illustrates wall design schematic from WUFI software.

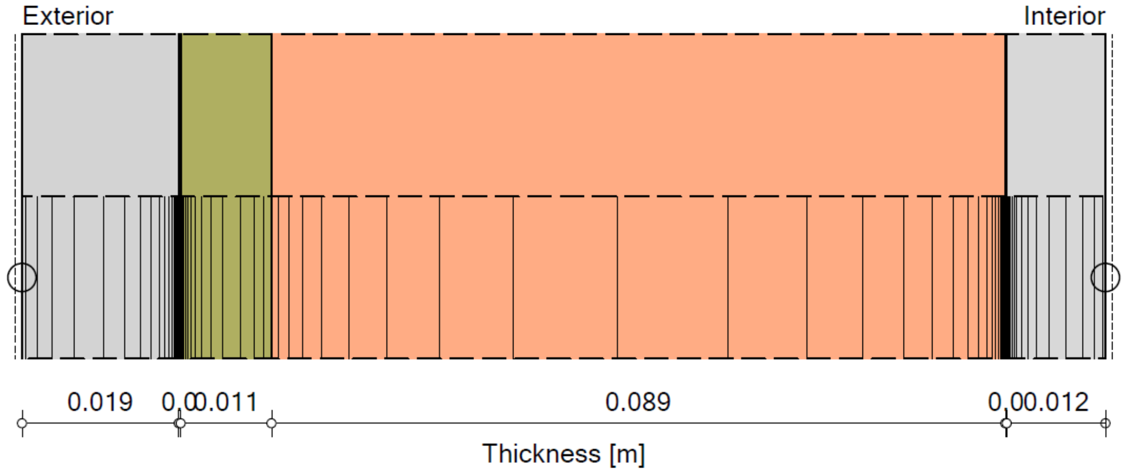

Figure 13: Wall design in WUFI

The Boundary conditions chosen for the simulation over the three-year period are shown in figure 14.

Exterior (Left Side)	
Location:	Vancouver; cold year
Temperature Shift:	0.0 °C
Orientation / Inclination:	South / 90 °
Nighttime radiation cooling:	Explicit Radiation Balance
Interior (Right Side)	
Indoor Climate:	ASHRAE 160P Heating only; 2,8 °C; 21,1 °C M.Rate 1.05E-4 kg/s; A.Ch.Rate 0.2 1/h; Vol. 500 m³ Humidity Ratio Wo -1.0000 kg/kg

Figure 14: Boundary conditions

3.3.1 Stucco properties changed for WUFI simulation

For the simulation, three properties in WUFI software were altered. Reference water content, free water saturation and water absorption coefficient. Water absorption coefficient value was obtained from the experiment work for all the specimens. As per the standard guidelines in WUFI, reference water content (w80) is water content in specimen at relative humidity of 0.8(80%). Due to limitations of the measuring procedures available, this value was considered as equivalent to water absorbed by specimens in first 15 minutes of the experimental run in Kg/m^3. Free water saturation (wf) is water content in specimen at relative humidity of 1(100%). Due to limitations of the measuring procedures available, this value was considered as equivalent to water absorbed by specimen at the end of the experimental run in Kg/m^3.

3.3.2 Material properties: Virgin stucco - normal temperature

Table 8: Properties of virgin Stucco

Property	Unit	Value
Bulk density	[kg/m³]	2261.63
Porosity	[m³/m³]	0.225
Specific Heat Capacity, Dry	[J/(kg K)]	840
Thermal Conductivity, Dry, 10°C	[W/(m K)]	0.399
Water Vapour Diffusion Resistance Factor	[-]	355.7
Reference Water Content	[kg/m³]	30.35
Free Water Saturation	[kg/m³]	198
Water Absorption Coefficient	[kg/(m² s^0.5)]	0.0053
Temp-dep. Thermal Cond. Supplement	[W/(m K²)]	0.0002

3.3.3 Material properties: Stucco - cold temperature treated

Table 9: Properties of cold temperature treated Stucco

Property	Unit	Value
Bulk density	[kg/m³]	2432.5
Porosity	[m³/m³]	0.225
Specific Heat Capacity, Dry	[J/(kg K)]	840
Thermal Conductivity, Dry, 10°C	[W/(m K)]	0.399
Water Vapour Diffusion Resistance Factor	[-]	355.7
Reference Water Content	[kg/m³]	26.75
Free Water Saturation	[kg/m³]	190
Water Absorption Coefficient	[kg/(m² s^0.5)]	0.0046
Temp-dep. Thermal Cond. Supplement	[W/(m K²)]	0.0002

3.3.3 Material properties: Stucco - hot temperature treated

Table 10: Properties of hot temperature treated Stucco

Property	Unit	Value
Bulk density	[kg/m³]	2165.9
Porosity	[m³/m³]	0.225
Specific Heat Capacity, Dry	[J/(kg K)]	840
Thermal Conductivity, Dry, 10°C	[W/(m K)]	0.399
Water Vapour Diffusion Resistance Factor	[-]	355.7
Reference Water Content	[kg/m³]	52.5
Free Water Saturation	[kg/m³]	225
Water Absorption Coefficient	[kg/(m² s^0.5)]	0.0105
Temp-dep. Thermal Cond. Supplement	[W/(m K²)]	0.0002

Chapter 4 Results

4.1 Results for Virgin specimens

In case of the base stucco sample i.e. virgin samples, the average water absorption coefficient as derived from the experimental results is 0.0053 $Kg.m^{-2}$. $s^{-1/2}$. Standard deviation of the average value of water coefficient from that of each individual samples is 0.0012. The sample calculations for how this values have been obtained is shown in the appendix.

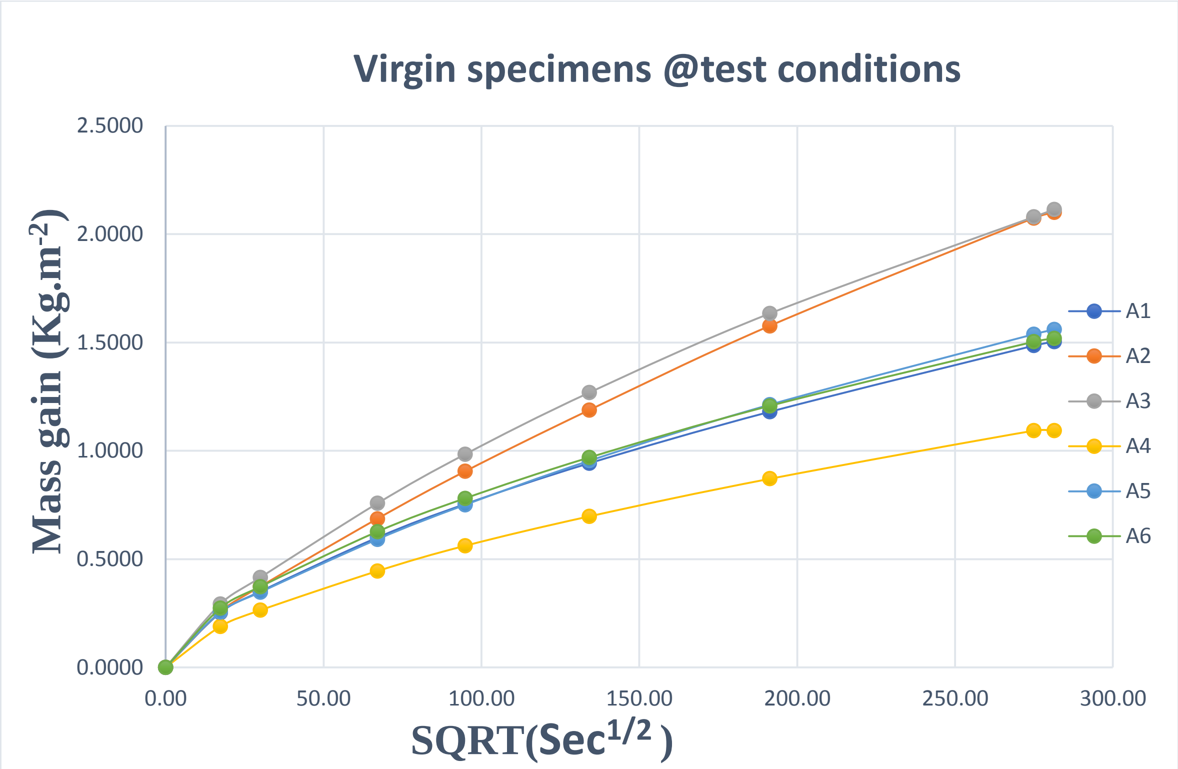

Figure 15: Results from water absorption test for virgin samples

Line equations for each specimen's Δm_t against the square root of the time ($\sqrt{t}$) graph is as below:

A1: y = 0.0046x + 0.3038 R^2 = 0.9961

A2: y = 0.0071x + 0.2197 R^2 = 0.9991

A3: y = 0.0070x + 0.3063 R^2 = 0.9972

A4: y = 0.0034x + 0.2302 R^2 = 0.9953

A5: y = 0.0050x + 0.2709 R^2 = 0.9974

A6: y = 0.0046x + 0.3305 R^2 = 0.9963

Results obtained from experimental work for the virgin samples is shown in following table.

Table 11: Water absorption coefficient of virgin samples

Specimen ID	Water Absorption Coefficient (Kg.m^{-2}. s$^{-1/2}$)
A1	0.0046
A2	0.0071
A3	0.0070
A4	0.0034
A5	0.0050
A6	0.0046
Average	**0.0053**
Standard Deviation	0.0012

4.2 Results for Cold temperature treated specimens

In case of the cold stucco sample, the average water absorption co efficient as derived from the experimental results is 0.0046 Kg.m^{-2}. s$^{-1/2}$. Standard deviation of the average value of water coefficient from that of each individual samples is 0.0004. The sample calculations for how this values have been obtained is shown in the appendix.

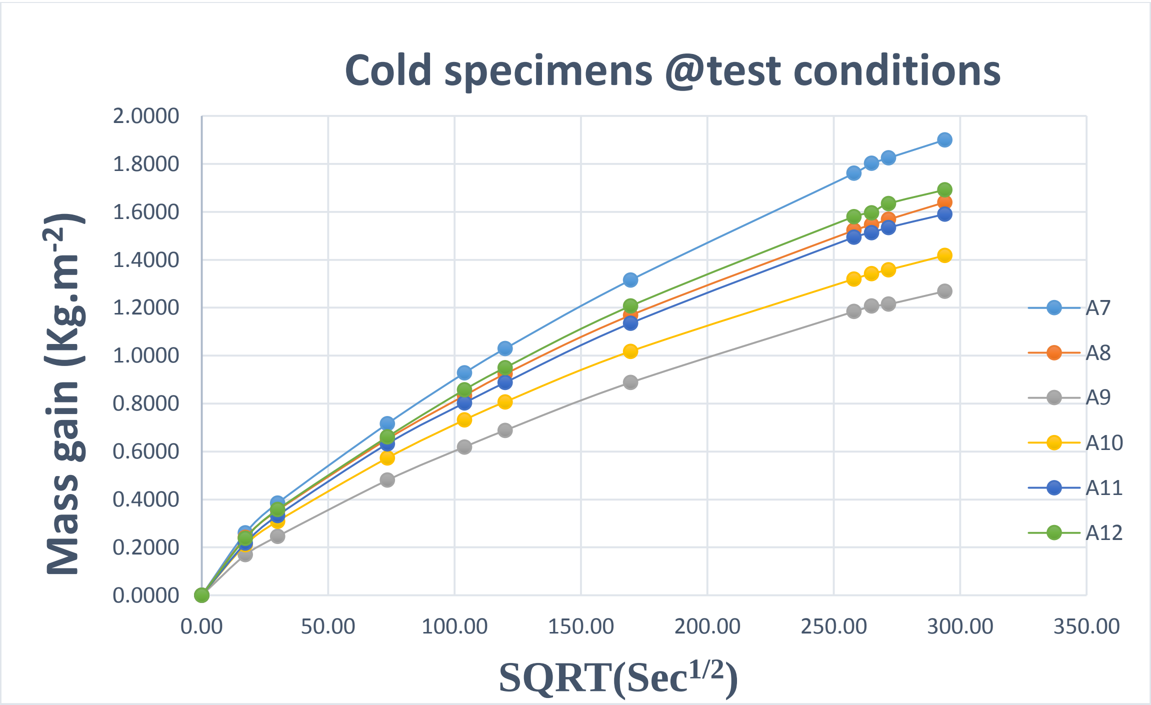

Figure 16: Results from water absorption test for cold temperature treated samples

Line equations for each specimen's Δm_t against the square root of the time ($\sqrt{t}$) graph is as below:

A7: $y = 0.0056x + 0.3397$ $R^2 = 0.9957$

A8: $y = 0.0047x + 0.345$ $R^2 = 0.9927$

A9: $y = 0.0038x + 0.2239$ $R^2 = 0.9956$

A10: $y = 0.004x + 0.3117$ $R^2 = 0.9921$

A11: $y = 0.0046x + 0.3187$ $R^2 = 0.995$

A12: $y = 0.0049x + 0.3403$ $R^2 = 0.9923$

Results obtained from experimental work for the Cold temperature treated samples is shown in following table.

Table 12: Water absorption coefficient of cold temperature treated samples

Specimen ID	**Water Absorption Coefficient ($Kg.m^{-2}. s^{-1/2}$)**
A7	0.0056
A8	0.0047
A9	0.0038
A10	0.0040
A11	0.0046
A12	0.0049
Average	**0.0046**
Standard Deviation	0.0004

4.3 Results for Hot temperature treated specimens

In case of the Hot stucco sample, the average water absorption co efficient as derived from the experimental results is 0.0105 $Kg.m^{-2}. s^{-1/2}$. Standard deviation of the average value of water coefficient from each individual sample is 0.0006. The sample calculations for how this values have been obtained is shown in the appendix.

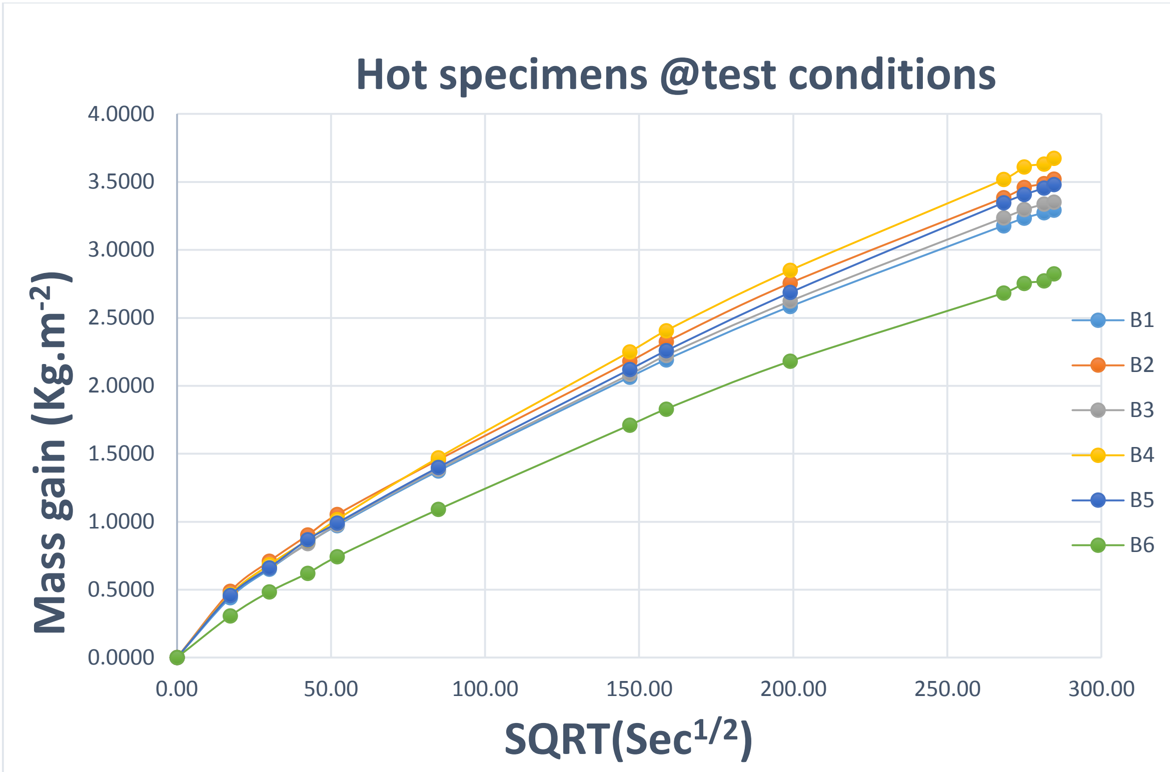

Figure 17: Results from water absorption test for hot temperature treated samples

Line equations for each specimen's Δm_t against the square root of the time ($\sqrt{t}$) graph is as below:

B1: $y = 0.0102x + 0.5079$ $R^2 = 0.9943$

B2: $y = 0.0109x + 0.5444$ $R^2 = 0.9956$

B3: $y = 0.0105x + 0.4997$ $R^2 = 0.9949$

B4: $y = 0.0116x + 0.4893$ $R^2 = 0.9941$

B5: $y = 0.0109x + 0.4752$ $R^2 = 0.9968$

B6: $y = 0.009x + 0.3337$ $R^2 = 0.9928$

Results obtained from experimental work for the Hot temperature treated samples is shown in following table.

Table 13: Water absorption coefficient of hot temperature treated samples

Specimen ID	**Water Absorption Coefficient (Kg.m^{-2}. s$^{-1/2}$)**
B1	0.0102
B2	0.0109
B3	0.0105
B4	0.0116
B5	0.0109
B6	0.0090
Average	**0.0105**
Standard Deviation	0.0006

Obtained water absorption coefficient values with specific stucco properties were entered in WUFI as described in Chapter 3. WUFI 1D simulation were performed for 3 years' period (2018-01-01 / 2021-01-01). Following results were observed for the total water content.

As seen from the table 14, small variation of water content inside wall assembly was observed. For the simulation performed using average water absorption coefficient of cold temperature treated specimens, least amount of water content was observed. While, for the simulation performed using average water absorption coefficient of hot temperature treated specimens, highest amount of water content throughout the simulation period was observed.

Table 14: Water Content [kg/m^3] in wall design

Total Water Content(Wall assembly)	Start	End	Min.	Max.
Wall design with Virgin stucco properties	1.66	0.98	0.76	1.66
Wall design with Cold stucco properties	1.60	0.96	0.74	1.6
Wall design with Hot stucco properties	2.08	1.16	0.92	2.08

Table 15 shows total water content inside stucco cladding for all three types of simulations performed. For simulation performed using value obtained from cold temperature treated specimens, least amount of water content was observed inside stucco cladding. While, for simulation performed using value obtained from hot temperature treated specimens, highest amount of water content inside stucco cladding was observed.

Table 15: Water Content [kg/m^3] in Stucco Cladding

Total Water Content(In stucco cladding)	Start	End	Min.	Max.
Virgin stucco	30.35	14.16	7.28	30.46
Cold stucco	26.75	12.77	6.25	26.86
Hot stucco	52.50	23.44	15.09	52.62

Chapter 5: Conclusion and future enhancement

From this water absorption test for the virgin samples and extreme temperature aged specimens, significant difference in the water absorption coefficient was observed. For the virgin samples, the average water absorption coefficient is 0.0053 $Kg.m^{-2}. s^{-1/2}$. When this samples are treated in 7 extreme cold temperature cycles (1 Cycle: 24 hours at -10°C, 24 hour at ambient 22±2°C) the average water absorption coefficient reduces to 0.0046 $Kg.m^{-2}.s^{-1/2}$. While when the samples are treated in 7 extreme hot temperature cycles (1 Cycle: 24 hours at 60°C, 24 hour at ambient 22±2°C), significant increment in water absorption coefficient (0.0105 $Kg.m^{-2}.s^{-1/2}$) of the stucco specimens is observed. In current experimental work, the water absorption coefficient of extreme hot temperature treated specimens is increased by 100% as compared to the virgin specimens. This can have significant impact on water content inside the stucco cladding of wood-frame wall assembly over the years.

Using the obtained values of water absorption coefficient, 1D WUFI simulations were performed. The results of simulations showed significant difference in water content inside the stucco cladding (for three types of specimens examined). Hot temperature treated stucco showed highest level of water content over 3 years' simulation.

For the future enhancement, Stucco samples can be treated at more practical temperature cycles for prolong period of time. This can better represent the effect of seasonal temperature changes on the water absorption coefficient of stucco cladding. Also the effect of extreme temperature cycles on other liquid moisture transport properties can be studied.

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Appendix:

A: Conditioning of the samples as per ASTM C1794-15:

Conditioning for the cured samples i.e. weight to be maintained within 0.1% of its total mass over 24h time. All weights are measured without clamps. Observed variation in weights measured over 24h was well within maximum variance allowed (0.1% of its weight i.e. approximately 0.25 grams).

Specimen ID	Weight (in grams)		
	4th April 2018	5th April 2018	6th April 2018
A1	238.58	238.31	238.18
A2	230.26	229.98	229.82
A3	232.55	232.30	232.17
A4	263.66	263.31	263.14
A5	231.61	231.26	231.09
A6	249.22	248.87	248.73
A7	236.52	236.28	236.11
A8	251.86	251.53	251.28
A9	256.06	255.80	255.60
A10	262.52	262.28	261.15
A11	242.92	242.62	242.47
A12	246.54	246.27	246.10

B. Contact Surface Area for all specimens

Specimen ID	Surface Area		Specimen ID	Surface Area	
	mm	m^2		mm	m^2
A1	2652	0.002652	A10	2652	0.002652
A2	2652	0.002652	A11	2704	0.002704
A3	2601	0.002601	A12	2601	0.002601
A4	2652	0.002652	B1	2738	0.002738
A5	2704	0.002704	B2	2706	0.002706
A6	2601	0.002601	B3	2706	0.002706
A7	2652	0.002652	B4	2706	0.002706
A8	2652	0.002652	B5	2706	0.002706
A9	2601	0.002601	B6	2706	0.002706

C: Result tables from experiment for Virgin specimens:

For virgin (23 ±2 °C) specimens						
TIME t (minutes)	Weight of specimens(in grams at specific time t)					
	A1	A2	A3	A4	A5	A6
0 (Initial)	297.87	289.20	291.71	321.91	290.82	307.84
5	298.54	289.88	292.47	322.41	291.51	308.55
15	298.80	290.19	292.79	322.61	291.76	308.81
75	299.46	291.02	293.68	323.09	292.42	309.47
150	299.87	291.60	294.27	323.4	292.85	309.87
300	300.37	292.35	295.01	323.76	293.4	310.36
610	301.00	293.38	295.96	324.22	294.1	310.98
1260	301.81	294.70	297.12	324.81	294.98	311.75
1320(Final)	301.86	294.77	297.21	324.81	295.04	311.79

Graph Table:

SQRT √T	Water Absorption ($Kg.m^{-2}$)					
	A1	A2	A3	A4	A5	A6
0.00	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
17.32	0.2526	0.2564	0.2922	0.1885	0.2552	0.2730
30.00	0.3507	0.3733	0.4152	0.2640	0.3476	0.3729
67.08	0.5995	0.6863	0.7574	0.4449	0.5917	0.6267
94.87	0.7541	0.9050	0.9842	0.5618	0.7507	0.7805
134.16	0.9427	1.1878	1.2687	0.6976	0.9541	0.9689
191.31	1.1802	1.5762	1.6340	0.8710	1.2130	1.2072
274.95	1.4857	2.0739	2.0800	1.0935	1.5385	1.5033
281.42	1.5045	2.1003	2.1146	1.0935	1.5607	1.5186

D: Result tables from experiment for cold temperature treated specimens

For cold temperature treated (-10 ±2 °C) specimens						
TIME t (minutes)	Weight of specimens(in grams at specific time t)					
	A7	A8	A9	A10	A11	A12
0(Initial)	294.32	308.90	312.93	320.58	300.43	304.08
5	295.01	309.54	313.37	321.14	301.02	304.7
15	295.34	309.84	313.57	321.4	301.33	305.01
90	296.22	310.63	314.18	322.1	302.14	305.8
180	296.78	311.11	314.54	322.52	302.6	306.31
240	297.05	311.35	314.72	322.72	302.83	306.55
480	297.81	312.00	315.24	323.28	303.5	307.22
1110	298.99	312.94	316.01	324.08	304.47	308.19
1170	299.10	313.00	316.07	324.14	304.52	308.23
1230	299.16	313.06	316.09	324.18	304.58	308.33
1440	299.36	313.25	316.23	324.34	304.73	308.48

Graph Table:

SQRT √T	Water Absorption (Kg.m^{-2})					
	A7	**A8**	**A9**	**A10**	**A11**	**A12**
0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
300	0.2602	0.2413	0.1692	0.2112	0.2182	0.2384
900	0.3846	0.3544	0.2461	0.3092	0.3328	0.3576
5400	0.7164	0.6523	0.4806	0.5732	0.6324	0.6613
10800	0.9276	0.8333	0.6190	0.7315	0.8025	0.8574
14400	1.0294	0.9238	0.6882	0.8069	0.8876	0.9496
28800	1.3160	1.1689	0.8881	1.0181	1.1354	1.2072
66600	1.7609	1.5234	1.1842	1.3198	1.4941	1.5802
70200	1.8024	1.5460	1.2072	1.3424	1.5126	1.5955
73800	1.8250	1.5686	1.2149	1.3575	1.5348	1.6340
86400	1.9005	1.6403	1.2687	1.4178	1.5902	1.6917

E: Result tables from experiment for hot temperature treated specimens

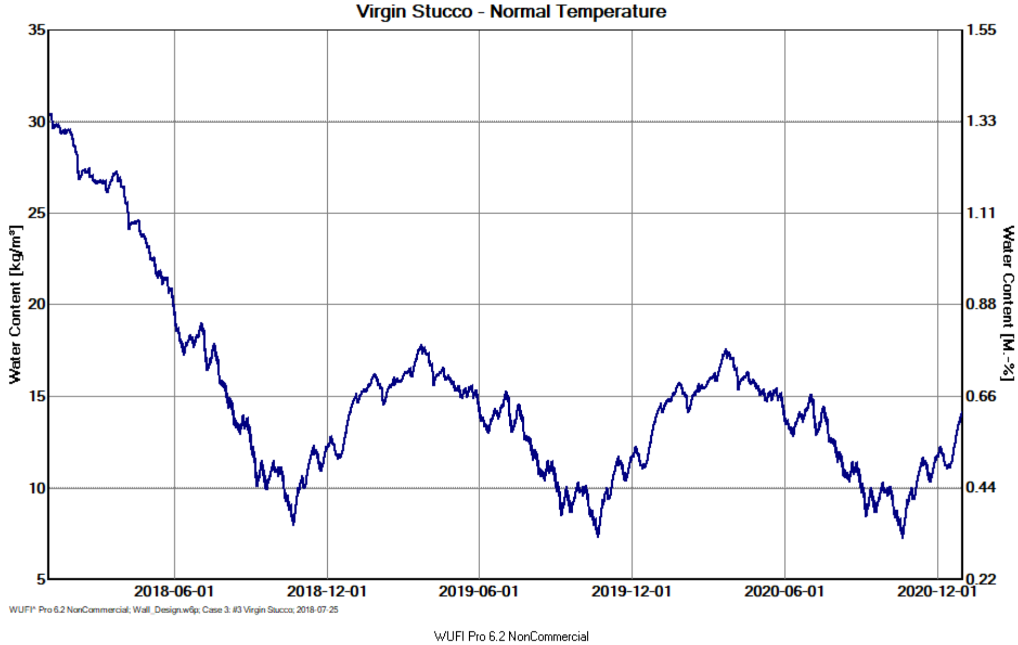
For hot temperature treated (+60 ±2 °C) specimens						
TIME t (minutes)	Weight of specimens(in grams at specific time t)					
	B1	B2	B3	B4	B5	B6
0 (Initial)	309.52	311.40	288.19	290.44	287.8	291.53
5	310.73	312.72	289.45	291.7	289.04	292.36
15	311.30	313.32	289.98	292.29	289.59	292.84
30	311.83	313.84	290.46	292.78	290.15	293.21
45	312.18	314.25	290.84	293.19	290.48	293.54
120	313.28	315.34	291.94	294.42	291.59	294.48
360	315.17	317.30	293.83	296.53	293.54	296.16
420	315.52	317.69	294.21	296.95	293.91	296.48
660	316.59	318.86	295.29	298.15	295.07	297.43
1200	318.22	320.56	296.95	299.96	296.86	298.79
1260	318.37	320.76	297.11	300.21	297.02	298.98
1320	318.48	320.84	297.22	300.27	297.15	299.03
1350	318.53	320.93	297.26	300.38	297.22	299.17

Graph table:

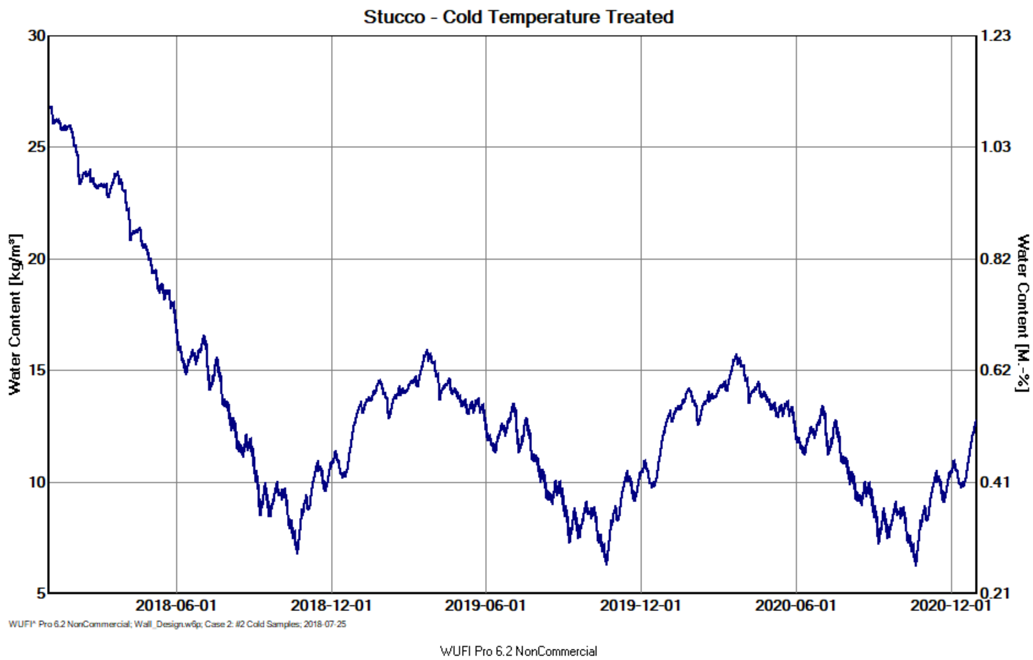
SQRT √T	Water Absorption (Kg.m^{-2})					
	B1	B2	B3	B4	B5	B6
0.00	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
17.32	0.4420	0.4877	0.4656	0.4656	0.4582	0.3067
30.00	0.6502	0.7094	0.6614	0.6835	0.6614	0.4840
42.43	0.8438	0.9015	0.8387	0.8646	0.8683	0.6207
51.96	0.9716	1.0530	0.9791	1.0161	0.9902	0.7427
84.85	1.3734	1.4558	1.3856	1.4706	1.4004	1.0900
146.97	2.0638	2.1800	2.0839	2.2502	2.1209	1.7107
158.75	2.1916	2.3241	2.2243	2.4054	2.2576	1.8290
199.00	2.5824	2.7564	2.6234	2.8487	2.6862	2.1800
268.33	3.1778	3.3845	3.2367	3.5175	3.3475	2.6825
274.95	3.2326	3.4584	3.2958	3.6099	3.4067	2.7527
281.42	3.2728	3.4880	3.3365	3.6321	3.4547	2.7711
284.60	3.2911	3.5212	3.3512	3.6727	3.4806	2.8229

F: Result graphs from WUFI simulations

Water content in Virgin stucco over the simulation period:



Water content in Cold temperature treated stucco over the simulation period:



Water content in hot temperature treated stucco over the simulation period: