Effect of Temperature on Water Vapor Transmission Properties of Building Materials

by

Gagan Pahwa
B.Tech, BBSB Engineering College, India, 2012

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of the Requirements for the Degree of

MASTER OF ENGINEERING

in the Department of Mechanical Engineering

Supervisory Committee

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Dr. Phalguni Mukhopadhyaya (Department of Civil Engineering)
Supervisor

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Departmental Member

Dr. Rodney Herring (Department of Mechanical Engineering)
Chair Member

Abstract

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With increasing focus on energy efficient and sustainable building envelopes, the need to define the heat-air-moisture transport (hygrothermal) properties of building materials accurately cannot be overemphasized. New techniques have been evolving and being examined for this purpose. The Modified Cup Method is one such technique to determine the water vapour transmission properties of building materials.

This project report describes the temperature dependency of water vapor transmission properties of four different building materials (interior finish board, engineered wood, wall sheathing membrane and roofing membrane). The tests were done following the procedure outlined in ASTM - E96 (Standard Test Methods for Water Vapor Transmission of Materials) [1]. The design and fabrication of the Modified Cup test assembly was done prior to the testing using SolidWorks software. The three different temperature levels considered were 3 ± 1°C, 22 ± 2°C and 50 ± 2°C. The results obtained from these tests were critically analysed and discussed in this report. In general, as expected, the results obtained from the tests show that the water vapor transmission rate of all four building materials considered in this study increases with temperature increment. However, the results obtained also show that water vapor permeability values do not have any consistent relationship with temperatures at which the tests were conducted.

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Acknowledgments

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Dedication

TO MY PARENTS AND BROTHERS

1. Introduction

The increasing demand for housing and growing interest in environmentally friendly building designs motivate the investigation of the hygrothermal performance of building materials. The water vapor permeability, air permeability, sorption/desorption, water vapor absorption rate, thermal conductivity and heat capacity are the key hygrothermal properties, which establish the hygrothermal performance index of the building material [1]. The building envelopes in Canada are subjected to various environmental factors such as extreme temperature, ranging from -40^0 C to +50^0 C, solar radiation, wind gusts and rain [1]. The design of the building envelope is based on the local climatic conditions. The hygrothermal response of building materials depend on the variability of the local temperature and relative humidity. As the thermal conductivity depends on the pressure difference, thermal conductivity depends on the local temperature and the water vapor permeability depends on the pressure difference that cause the thermal vapor response through the material. The temperature gradients allow the flow of heat and air movement through the building materials. In order to maintain desired building envelope performance, the heat and moisture transport properties should be evaluated and determined to select the appropriate building material.

Moisture movement effects the performance of the building envelopes [3]. The moisture management strategies should be implemented to ensure long-term durability and serviceability of exterior building envelopes. The basic moisture transport mechanisms are: (1) The water vapor diffusion due to the pressure difference (2) capillary suction in the porous material (3) water vapor displacement due to the air flow (4) liquid water flow due to air pressure gradients (includes the wind driven rain). Table 1 shows the driving forces for moisture transport mechanism in liquid and vapor phase. In order to achieve effective moisture management techniques, the air barriers, vapor barriers, and inner sheathing materials have to perform effectively as per design specifications [3].

Table 1 - Moisture transport mechanisms and driving forces [4]

Phase	Transport Methods	Driving Forces
Liquid	Surface Diffusion	Relative Humidity or Moisture Content
	Capillary Suction	Suction Pressure
	Hydraulic Flow (Liquid flow)	Pressure Gradients
Vapor	Effusion (Molecular Transport)	Vapor Pressure
	Water Vapor Diffusion	Temperature Gradient and Total Pressure
	Convection	Total Pressure Gradient
	Solution Diffusion	Vapor Pressure

Water vapor permeability (WVP) is the common parameter used to evaluate the moisture transfer rate through building materials[4]. Laboratory tests to measure water vapour permeability of building materials are conducted at ambient room temperature (22 ± 1^0C). However, in real life, building envelopes are exposed to a wide range of temperature and very little is known about the effect of temperature on the water vapour transmission properties of common building materials [1]. The effect of temperature on the water vapor transmission properties of building materials is examined in this study. The obtained test results are compared with the results from the previous studies.

Four building materials under consideration are: (1) Wall sheathing membrane, (2) roofing membrane, (3) Interior finish board and (4) Engineered wood (3/8 inch). The three temperature ranges considered are: (1) low temperature (2 ± 1^0C), (2) room temperature (22 ± 2^0C) and (3) high temperature (50 ± 2^0C). These temperatures represent above freezing temperature to which the building envelope response to.

2. Objective and Project Layout

The aim of this project is to investigate the influence of temperature on water vapor transmission properties of four different building materials using modified cup method (see section 3.3). The temperature is the major factor that increases the mobility of the water molecules which results in high water vapor transmission [5]. Equation 1 represents the Fick's law which shows the relation between the temperature (T) and water vapor transmission (WVT) rate along with relative humidity (RH).

$$WVT = \mu\,(\mathrm{RH}, \mathrm{T})\,\frac{\Delta \mathrm{P}}{\Delta \mathrm{X}} \qquad (1)$$

Where WVT ($kg/m^2.S$), μ is water vapor permeability and a function of relative humidity (RH) and temperature (T), ΔP is change in water vapor pressure and ΔX is change in the distance. In a study conducted by Kumaran [6], it was observed that the water vapor permeability of the hygroscopic materials significantly increases with the increase in the relative humidity whereas the water vapor permeability of the non-hygroscopic materials is not affected by the relative humidity variation. Presently, many numerical tools are considering the water vapor permeability as the function of relative humidity in order to calculate the design values of the building materials. Previous studies suggested that the activation energy is a function of temperature [1], which is developed from the kinetic theory of chemical reaction as shown in equation 2:

$$\mu = \mu_0\, e^{(-E/RT)} \qquad (2)$$

Whereas R = gas constant, T = absolute temperature, E = activation energy and μ_0 = permeability for $T=\infty$

In this project modified cup test method has been used for water vapour permeability measurement. In modified cup test method temperature variation does not impact the relative humidity conditions across the specimen, unlike conventional cup method.

Figure 1 shows the project layout and the methodology adopted for testing procedure. The project layout is divided into four phases which are (1) Understanding the literature of the basics of heat and moisture properties, (2) Experimental setup which involves the test material setup and equipment setup, (3) Testing after regular intervals using standardized calibrated weight scale and (4) Data analysis of the results using excel and calculations of the WVP. This project is completely focused on evaluating the effect of temperature on the water vapor transmission properties of building materials with the improved design of the modified cup method as per standard prescribed in ASTM E96 (Standard Test Methods for Water Vapor Transmission of Materials) [2].

3. Literature Review

The number of experiments had been performed to determine the water vapor transmission properties of the building materials. The recent studies also conclude the dependence of water vapor permeability on temperature and humidity. The various temperature ranges had been adopted during the recent experiments. The temperature dependency of water vapor permeability has been great interest for the researchers.

The study of S.C. Chang, N.B. Hutcheon [7] concluded the effect of the temperature and relative humidity on the water vapor permeability and discussed about the permeability coefficient and average permeability of building materials which are asphalt saturated Wall sheathing membrane, asphalt saturated sheathing felt and Kraft Wall sheathing membrane. The study concluded that the permeability curve can be generated at the 20% increase of the relative humidity in the isothermal conditions. The water vapor permeability calculated for three building materials shown that the water vapor permeability increases with increase in temperature and relative humidity under isothermal conditions.

In one of the previous study to determine the temperature dependency of water vapor transmission properties of building materials with use of new version of modified cup method from 7ºC to 43 ºC and 50% average relative humidity [1]. Interior finish board and Fibre board were used as building material to conduct experiment for investigating the effect of temperature on water vapor transmission properties based on the standard ASTM E96 [2]. The study concluded that the water vapor transmission rate increases with increase in temperature while the water vapor permeability is not affected with the temperature condition.

Another study [8] was conducted to investigate the temperature effect on the moisture permeability of four commonly used building materials – plasterboard, foam insulation, plywood and medium density fibreboard (MDF) using the standard CEN Cup test method. The building materials were tested at three different temperatures. The study concluded that the temperature effect on permeability is depends on the relative humidity properties of the material. For plasterboard and phenolic foam insulation, the moisture permeability is not affected by the temperature. But their significant variation in the moisture permeability with change in temperature for the MDF and plywood. The study also suggested that the viscosity plays important role in temperature variation as decrease in the viscosity caused by an increase in temperature which leads to increase in the differential permeability.

Valovirta and Vinha [9] reported experimental results for the commonly used building materials in Nordic climatic conditions using wet cup method. The common building materials- interior boards, sheathing membranes and thermal insulation were studied at different relative humidity levels (35%, 50%, 70% and 90%) along with three different temperature ranges (-1 ºC, 5 ºC, 23 ºC respectively. The experiment results show increase in water vapor permeability over 50% relative humidity at constant temperature conditions.

4. Background

4.1 Definitions

I. **Water Vapor Transmission:** The water vapor transmission is the rate at which water vapor passes through the unit area of the specimen per unit time under the specified conditions of temperature and relative humidity of the surface.

$$\boldsymbol{WVT = \frac{G}{tA} = \frac{(G/t)}{A}} \tag{3}$$

Where G (kg) is weight change of the desiccant or water chamber. t (s) time, G/t (kg/s) slope of the straight line and A is the test area (mm^2) [1].

II. **Water Vapor Permanence (WVPR):** The water vapor permanence is the ratio of the water vapor transmission rate to the water vapor pressure difference across the material [1].

III. **Water Vapor Permeability (WVP):** The water vapor permeability is the product of the water vapor permanence and thickness (d) of the material [4].

IV. **Water Vapor Resistance (WVR):** The water vapor resistance of a building material is the reciprocal of the Water Vapor Permanence [4].

$$WVR = \frac{1}{WVPR} \tag{4}$$

Resistance due to Still Air Layer

If the thickness of the still air layer is present between the desiccant and test chamber or water chamber and test specimen is known, then the water vapor resistance can be calculated using equation 5 of permeability as determined by Schirmer [10]

$$\delta_a = \frac{2.305 \times 10^{-5}}{R_v\, P\, T}\, P_0 \left(\frac{T}{273.15}\right)^{1.81} \tag{5}$$

Where δ_a (kg/m.s.Pa) is the water vapor permeability of the still air, P_0 is standard atmospheric pressure, i.e. 101325 Pa (760 mm of Hg), P is ambient air pressure (Pa), T is the temperature (K) and R_v is the ideal gas constant for water (461.5 J. K-1.kg^{-1}).

Resistance Due to Specimen Surface

The total surface resistance offered by two surfaces is known to be approximately 4 x 10^7 Pa.s.m^2.kg^{-1}[1]. Equation 6 represents Lewis relation which describes the surface resistance (i.e. inside and outside of the test specimen) [4].

Corrected WVR of the specimen = (Calculated WVR from Equation 4) – (Resistance offered due to the still air from Equation 5) along with specimen surface (i.e. 4 x 10^7 Pa.s.m^2.kg^{-1}).

$$\mathrm{WVR}_{\mathrm{corrected}} = \frac{1}{WVPR} - \frac{1}{\delta_a} - S_n \tag{6}$$

Where;

S_n = resistance offered by specimen surface (Pa.s.m^2.kg^{-1})

$$\text{Corrected water vapor permanence of the specimen} = \frac{1}{WVR_{Corrected}} \tag{7}$$

Corrected water vapor permeability (WVP) of the material (Kg m^{-1}.s^{-1}.Pa^{-1}) = (Corrected WVPR of the specimen) x (thickness of the specimen) i.e.

$$\mathrm{WVP}_{\mathrm{corrected}} = \mathrm{WVPR}_{\mathrm{corrected}} \times d \tag{8}$$

4.2 Description of Building Products

a) **Interior finish board**: The Interior finish board is the interior building layer which is usually available as 4 x 8 ft boards of either ½ or ¾ inch thickness.

b) **Engineered wood**: The Engineered wood has the different nominal thickness. The product used in this project has a thickness of 3/8 inch.

c) **Wall sheathing membrane:** The Wall sheathing membrane is used between the exterior wall sheathing and exterior cladding to provide an air barrier and to resist the moisture movement. The Wall sheathing membrane used in this project has the thickness of 0.25 ± 0.2 mm and is cut into the size of the test chamber.

d) **Roofing Membrane paper:** The roofing membrane paper is the main component of a shingle roofing system and acts as the protective layer of underlayment. The thickness of roofing membrane is 0.20 ± 0.01 mm.

The densities and thickness of the building material are as shown in Table 2.

Table 2 - Measured thickness and densities of the products [4]

Materials	Thickness (mm)	Bulk Density (kg/m^3)	Dry Density (kg/m^3)
Engineered wood	12.58 ± 0.40	456 ± 30	429 ± 25
Interior finish board	12.60 ± 0.11	592 ± 5	569 ± 18
Wall sheathing membrane	0.25 ± 0.01	--	--
Roofing membrane	3.20 ± 0.01	900	--

4.3 Modified Cup

The modified cup method is the technique which is used to determine the water vapor permeability. ASTM E96 [2] is used as the reference to adopt the correct procedure for the process evaluation. In modified cup method, the sample is sealed between the desiccant chamber and water chamber. The experimental setup is placed in the controlled environment as per specified conditions. The weight of the water cup and desiccant cup is determined after regular intervals which further allows the data analysis and calculations based on the weight gained by desiccant and weight lost by the water cup. Overall the process needs continuity and periodic measuring of the weight of the cup for determining the water vapor transmission properties. The starting phase of the process takes significant time to saturate as initial weight changes are not the same and initial conditions change quickly.

In modified cup test method, both dry cup and wet cup are parts of a single test assembly (Figure 2) placed in a controlled temperature condition. Furthermore, the water cup section produces the 100% relative humidity on one side of the test material and the dry cup represents the 0% relative humidity. The basic principle of the dry cup and wet cup method are shown in Figure 1.

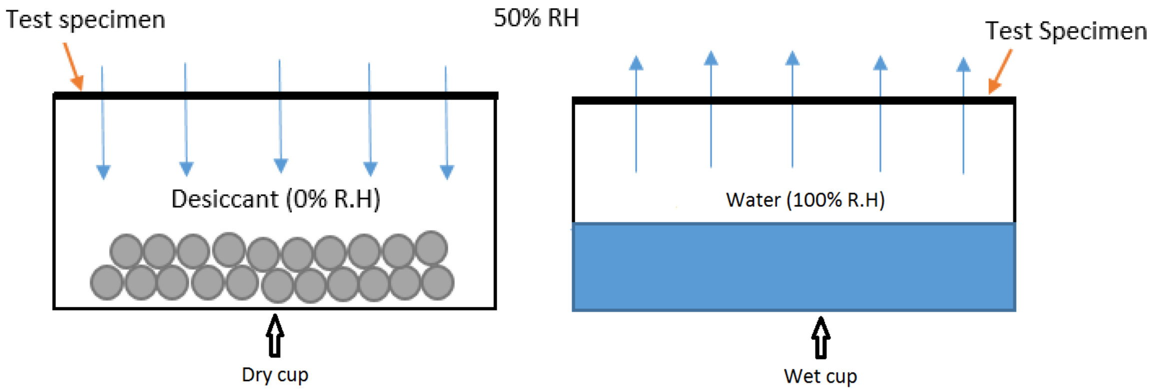

Figure 1 - Conventional dry cup and wet cup method

The cup is made of PVC and the test material is placed in the test chamber using mixture of 60% paraffin and 40% molten beeswax under a temperature (≈ 135^0 C) as per ASTM E96 standards [2]. The calcium chloride is used as the desiccant in the top chamber while the distilled water is used as moisture source in the water chamber at the lower side. To prevent the water vapor transport through joints, O rings are used between the containers to give the proper sealing. The whole modified cup is assembled tightly by two aluminum plates which are held together by bolts (Figures 3 and 4). Figure 4 shows the parts of the modified cup whereas Figure 5 shows the assembly of the modified cup. Figure 5 shows the application of the mixture of molten beeswax and paraffin between the test chamber and test material. After applying the molten wax around the test specimen, the molten wax was dried out for five minutes. The calibrated weighing scale was used to weight the chambers of the modified cup as shown in Figure 6.

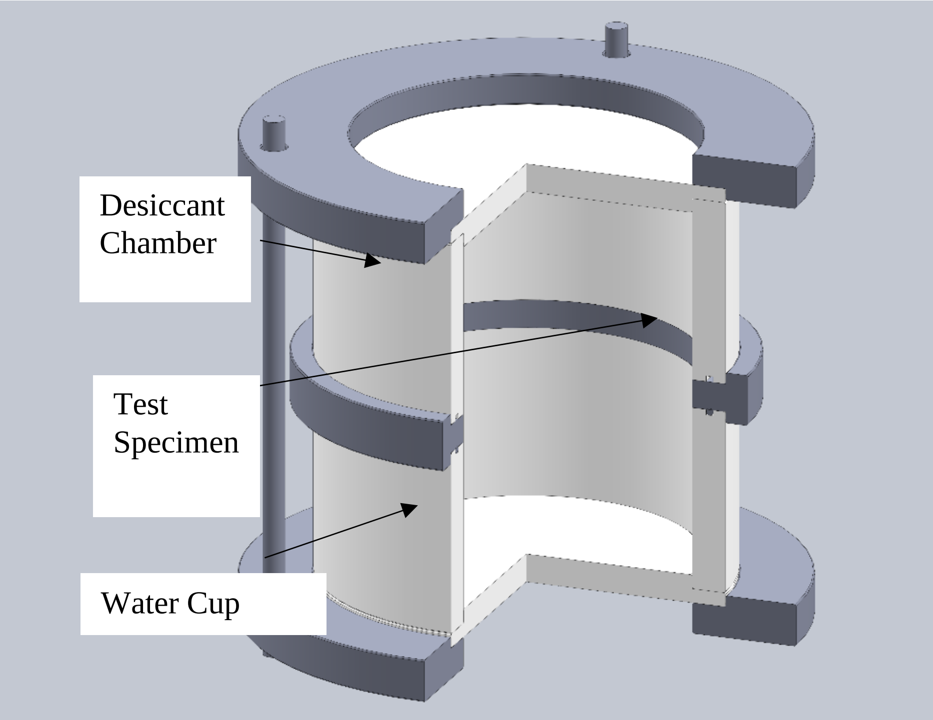

Figure 2 - Modified cup assembly [1]

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5. Experimental Methodology

5.1 Experiment Setup

The modified cup method has been used in this experiment to evaluate the water vapor permeability of Interior finish board, engineered wood, building sheathing paper and roofing membrane at three different temperature ranges; 2 ± 1^0C, 22 ± 2^0C and 50 ± 2^0 C.

The methodology for this experiment is based on the ASTM E96 which is extensively used for measuring the water vapor permeability under isothermal conditions. For each separate material, two modified cup test assemblies were used. Once the test specimen is ready, then the two-filter papers was bolted on the desiccant chamber. The filter paper had uniformly distributed holes of 0.2mm diameter. These holes allow uniform water vapor transmission through the filter.

The mass and the dimensions of the modified cup were noted prior to the experimental program. Calcium chloride was used as the desiccant material. After the calcium chloride absorbed moisture to saturation, it was dried out in the oven to achieve 10% dry weight. The calcium chloride was placed in the oven at the temperature of 80 - 110^0C for 24 hours. After the drying process, the calcium chloride was ready to be used as a desiccator [2].

In the modified cup method, the water vapor transmission properties can be calculated seperately from two sets of data. One way is from the data on the weight change of the water cup and the other way is from the data on the desiccant cup with respect to time. If the readings are taken accurately, then the water vapor transmission properties from these set of results should be same. Furthermore, when the steady state of water vapor transmission is achieved then the weight gained by the desiccant chamber should be same as the weight lost by the water chamber.

Figure 3 - Modified cup disassemble parts

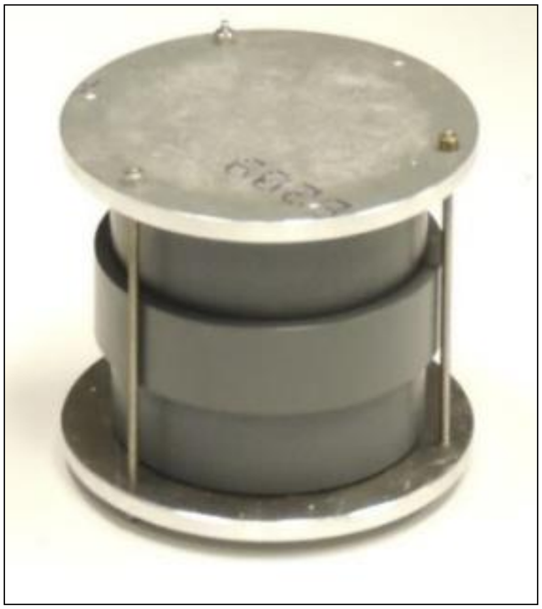

Figure 4 - Modified cup apparatus

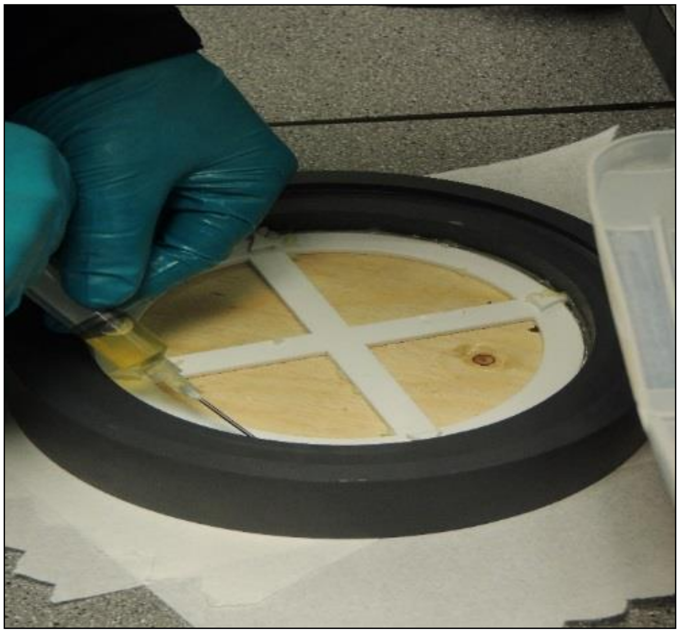

Figure 5 - Shows the molten wax process around the test specimen to seal the test material

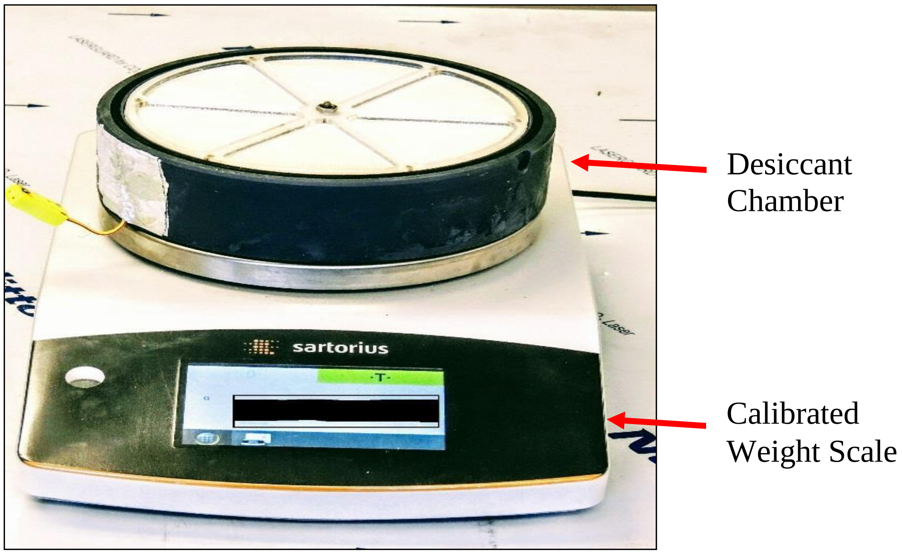

Figure 6 - Desiccant chamber on the weighing machine

The proper setting of the experimental setup was necessary prior to testing. During the testing, the air ventilation diffusers were affecting the water vapor transmission rate by supplying different air flow inside the lab. In order to identify the errors, the modified cup test was performed under the air diffusers and the water vapor transmission was affected. The readings in the data collector suggested the significant variability of the temperature. To achieve reliability in results, the modified cups were placed in a controlled temperature chamber by placing them inside a polyurethane box. The readings were taken at regular intervals.

The materials used for the construction of the modified cup test assembly and the peoperties of Calcium Chloride are shown in Tables 3 and 4 respectively.

Table 3 – Material used for Equipment Parts [4]

Equipment parts	Material
Desiccant chamber, Water chamber	Poly Vinyl Chloride
Foam box	Polyurethane
Top and bottom plates	Aluminium
Test specimen chamber	Poly Vinyl Chloride
Sealing agent	60% Paraffin and 40% Bees Wax
Filter paper	Cellulose B-1-070
Nuts and bolts	Nylon 66

Table 4 - Properties of $CaCl_2$

Properties	Desiccant Material ($Cacl_2$)
Thermal conductivity	0.54 W/m.k
Specific heat	670 J/kg.s
Specific density	2.15 g/ml

Calcium chloride as the desiccant in the dry cup and distilled water as the moisture source in the wet cup which is filled in water chamber about 15mm below the top surface as per ASTM E96 standard [2]. The drying capacity of calcium chloride might reduce after a certain limit that is 10% change of its dry weight after absorbing the water. In order to use the calcium chloride, it needs to be dried again in the oven with a specific condition as per ASTM E96 [2]. The test material should be properly clean and have no surface defects. The CNC machining of the test material should be uniform on all sides. Vernier Caliper was used for measuring the thickness of the test material for calculating results as shown in Figure 7.

Figure 7 - Measuring the thickness of roofing membrane using Vernier caliper

5.2 Test Conditions

Three different temperature conditions were selected i.e. 2 ± 1^0C, 22 ± 2^0C and 50 ± 2^0 C. The room temperature was maintained using an insulated enclosure made of polyurethane having a modified cup inside it (see Figure 8). For the low temperature, the temperature was maintained using the cooling chamber. The cooling chamber used to maintain the temperature at 2 ± 1^0C and temperature of 50 ± 2^0 C were maintained using an oven. The oven and cooling chamber both have the capacity to attain temperature within setup point $\pm 0.1^0$C [6]. The calibrated scale was used for the test on the uniform surface and weight of the specimen and test chamber prior to the testing as prescribed under ASTM E96 [2].

5.3 Experimental Procedure

The test procedure was performed under the criteria prescribed in ASTM E96 [2]. The dry calcium chloride, properly sealed test material, distilled water, calibrated weighing scale (sensitivity 0.01 grams) and data logger, for collecting the relative humidity and temperature readings, were necessary to obtain prior to the project. The procedure for the testing is divided into several steps which are as follows:

a) Measure the weight of the desiccant chamber including the calcium chloride in it as per ASTM E96 standards. Water cup chamber filled with distilled water to a reference level of 24 ± 1mm to the surface of the water chamber. The weight of each chamber along with the time was recorded to analyze the results with respect to time [2].

b) The weight of the test specimen was measured simultaneously.

c) After weighing of all three chambers, the modified cups (wet at bottom and dry at top) were bolted tight with aluminum plates together and placed in the polyurethane box along with data logger to measure the relative humidity and temperature at regular intervals. The test setup is shown in the Figure 8.

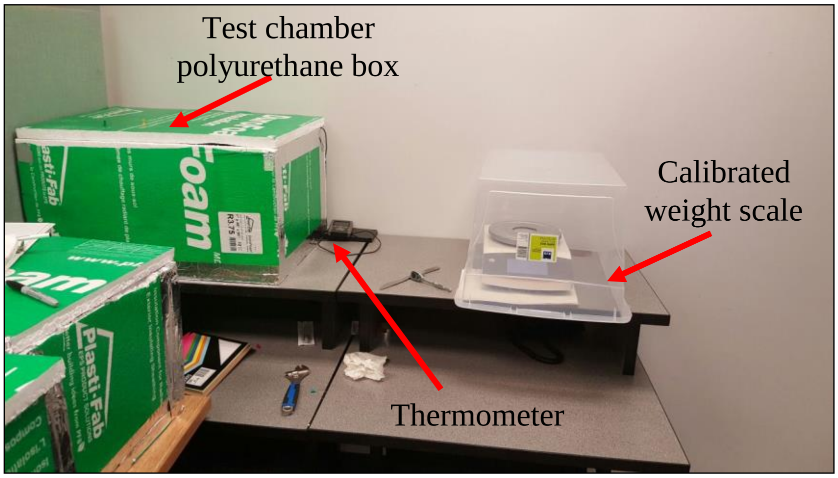

Figure 8 – Experimental setup

d) The weight changes were significantly higher during the initial readings as the test material took time to saturate during the starting phase. For the calculations, the first five rounds of readings were neglected due to the unsaturated state of the specimen.

e) To achieve the steady state of measurements, the R^2 (linear regression coefficient) should be close to 0.99. The water vapor transmission rate is measured by the slope of the straight line.

f) The two individual modified cups were placed in three different conditions and the modified cups were disassembled to take measurements. During the whole process, there are chances of losses during the dismantling process. To avoid heavy losses, the disassembling process should rapid and carefully performed.

g) The next step was to record the values in the excel worksheet and plot the graphs as the change in the weight of desiccant versus change in the weight of the water chamber against the time elapsed.

6. Analysis of Results

The test results are derived from the best fit linear regression of six test data points. The result of R^2 for the six steady-state test data points was approximately 0.99. Following corrections were applied to calcite the water vapour permeability and permeance values [4].

I. Correction based on resistance to the steady air layer.

II. Correction due to specimen surface resistance.

The calculation process and principles are outlined in the following sections.

6.1 Water Vapour Transmission

The water vapor transmission is the result of the graph plotted between the desiccant and the water cup weight change plotted against the time elapsed. The set of the six data points forming a straight line indicates the steady-state water vapor transmission. The slope of this line is the measure of the water vapor transmission rate (WVT). The value of the slope was later used to calculate the permeance and permeability [1].

The water vapor transmission rate is determined by using the following equation as:

$$WVT = \frac{G}{tA} = \frac{(G/t)}{A} \tag{9}$$

Where;

G = mean weight change of the desiccant or distilled water.

t = time (s)

G/t = slope the six points line (kg/s)

A = test area, cup mouth area (mm^2)

6.2 Water Vapor Permeance

Water vapor permeance (WVPR) is derived from water vapor transmission rate as:

$$WVPR = \frac{WVT}{S(R_1 - R_2)} \tag{10}$$

Where;

WVT = water vapor transmission rate (kg/s.m^2)

S = saturation water vapor pressure at test temperature (Pa)

R_1 = relative humidity at moisture source (water chamber) as fraction

R_2 = relative humidity at the water vapor sink (desiccant chamber) also expressed as fraction

6.3 Water Vapour Resistance

The water vapor resistance WVR (m^2.s.Pa/kg) is the reciprocal of the water vapor permeance of the building component. [1]

$$WVPR \;\; = \; = \frac{1}{WVR} \tag{11}$$

The corrections are required for the results afterward, which eliminate the errors. The corrections are as:

Due to the still air layer

$$\delta_a = \frac{2.305 \times 10^{-5}}{R_v\, P\, T}\, P_0 \left(\frac{T}{273.15}\right) \tag{12}$$

Where;

δ_a = Permeability of still air (kg.m^{-1}.s^{-1}.Pa^{-1})

T = temperature (K)

P_o = standard atmospheric pressure, i.e. 101325 Pa (760 mm of Hg)

R_v = ideal constant for water, i.e. 461.5 J.K^{-1}.kg^{-1}

P = ambient pressure (Pa)

Resistance offered by still air (AR) is,

$$AR \; = \frac{1}{\partial_a} \tag{13}$$

Where;

∂_a = the permeability of still air (kg m^{-1} s^{-1} Pa^{-1}).

Resistance due to specimen surface

The specimen surface offered resistance which is significant and can be determined by using the Lewis equation. In the case of the modified cups testing system, the total specimen surface resistance offered by the both surfaces are approximately 4 x 10^7 Pa.s.m^2 Kg^{-1}[1].

The effective WVR of the specimen = WVR – resistance due to still air and specimen surface WVR effective is

$$\text{WVR}_{\text{effective}} = \frac{1}{WVPR} - \frac{1}{\partial_a} - S_R \quad (14)$$

S_R = resistance offered by the test specimen surface

Corrected WVPR of the specimen = 1/ effective WVR of the specimen surface

$$WVPR_{corrected} = \frac{1}{WVR_{Effective}} \quad (15)$$

Then the corrected water vapor permeability (WVP) of the material is calculated by the product of the corrected WVPR of the specimen and thickness of the specimen. i.e.

$$\text{WVP}_{\text{corrected}} = \text{WVPR}_{\text{corrected}} \text{ x d} \quad (16)$$

Where;

d= thickness of the test material (mm).

7. Test Results and Discussion

The water vapour transmission properties were derived from the weight change of the desiccant and using the methodology described in the previous section. The modified cup is combination of both dry cup and wet cup and should generate the same water vapor transmission properties [11]. The water vapor transmission rate from the wet cup is not constant due to the vapour losses during weight measurement. Therefore, the dry cup results were used for calculating water vapor transmission properties.

As would be expected, in general, the higher temperature leads to higher rate of water vapour transmission rate (WVT). At higher temperature, the rate of WVT is much rapid than at the lowest temperature. As the water vapor transmission rate is a measure of mass transfer rate per unit area so it does not show the effect of driving forces such as vapour pressure difference. The water vapor permeability is the water vapor transfer property under unit driving force through unit area and represented as water vapor transfer coefficient.

7.1 Results at 3±1°C (Low temperature)

Water vapor transmission rate, water vapor permeance and water vapor permeability of the building materials at 3°C are shown in Table 5 and Figure 9.

Table 5 - WVT rate, WV permeance and WV permeability of test materials at 3°C

Test Material	**Water Vapor Transmission gm/(sec.m^2) 10^{-3}**			**Water Vapor Permeance gm/(s.m^2.Pa) 10^{-7}**		**Water Vapor Permeability gm/(s.m.Pa) 10^{-8}**		
	Modified Cup 1	Modified Cup 2	Mean	Modified Cup 1	Modified Cup 2	Modified Cup 1	Modified Cup 2	Mean
Interior finish board	6.57	7.39	6.98	8.25	11.10	10.79	12.14	11.47
Engineered wood	1.23	0.90	1.07	18.39	13.4	2.39	1.75	2.07
Wall sheathing membrane	1.48	1.48	1.48	22.0	22.1	5.52	5.52	5.52
Roofing Membrane	1.74	1.59	1.67	2.60	2.37	5.21	4.75	4.98

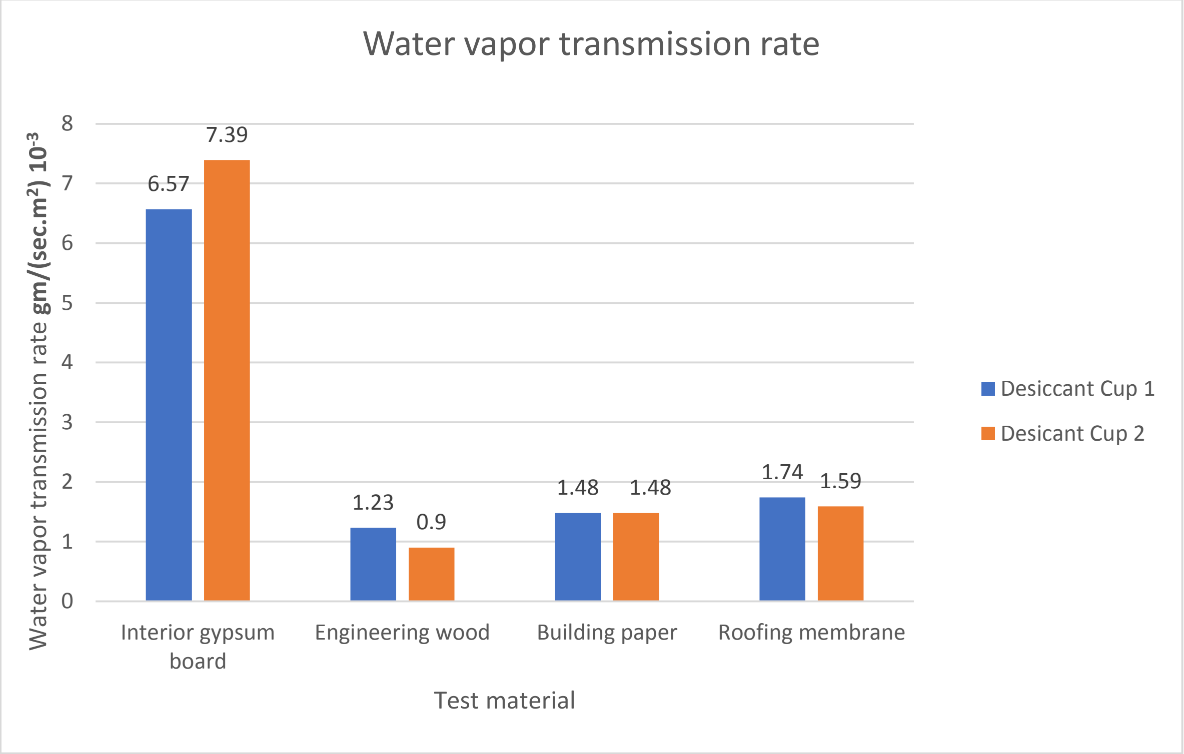

Figure 9 - Comparison of WVT of building materials at 3±1^{0}C (Modified cup 1 and modified cup 2)

7.2 Results at 22±2°C (Room Temperature)

Four materials were tested at the room temperature i.e. 22^{0}C. Table 6 shows the WVT rate, WV permeance and WV permeability of the building materials at 22^{0}C for specimen 1 and specimen 2 respectively and results are shown in Table 6 and Figure 10.

Table 6 - WVT rate, WV permeance and WV permeability of test materials at 22±2°C

Test Material	**Water Vapor Transmission $gm/(sec.m^2)10^{-3}$**			**Water Vapor Permeance $gm/(s.m^2.Pa)\ 10^{-7}$**		**Water Vapor Permeability $gm/(s.m.Pa)\ 10^{-8}$**		
	Modified Cup 1	Modified Cup 2	Mean	Modified Cup 1	Modified Cup 2	Modified Cup 1	Modified Cup 2	Mean
Interior finish board	4.93	4.10	4.52	17.7	14.7	1.95	1.62	1.79
Engineered wood	8.70	7.3	8.00	3.13	2.66	0.97	0.41	0.69
Wall sheathing membrane	2.47	2.14	2.31	8.87	7.68	2.21	1.92	2.07
Roofing Membrane	2.46	2.31	2.39	8.86	8.24	1.77	1.66	1.72

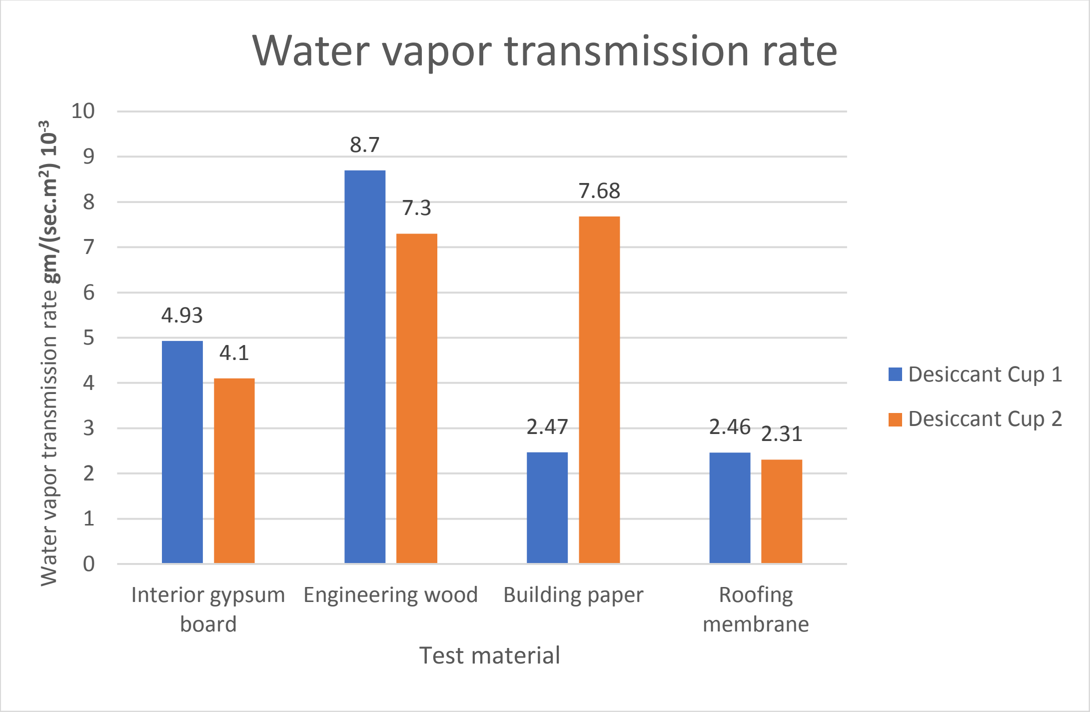

Figure 10 - Comparison of WVT of building materials at 22±2 °C (Modified cup 1 and modified cup 2)

7.3 Results at 50±2°C (High Temperature)

The final part of the testing process was to test the four building materials in the high-temperature (≈50^0 C). The test results (see Table 7 and Figure 11) are showing the high water vapor transmission rate than the lower temperature.

Table 7 - WVT rate, WV permeance and WV permeability of test materials at 50±2 °C

Test Material	Water Vapor Transmission gm/(sec.m^2)10^{-3}			Water Vapor Permeance gm/(s.m^2.Pa)10^{-7}		Water Vapor Permeability gm/(s.m.Pa)10^{-8}		
	Modified Cup 1	Modified Cup 2	Mean	Modified Cup 1	Modified Cup 2	Modified Cup 1	Modified Cup 2	Mean
Interior finish board	13.64	13.80	13.72	11.06	11.19	1.21	1.23	1.22
Engineered wood	9.5	11.9	10.70	0.77	0.97	0.1	0.13	0.12
Wall sheathing membrane	8.71	9.37	9.04	7.06	7.60	1.77	1.90	1.84
Roofing Membrane	8.38	8.88	8.63	6.80	7.20	1.36	1.44	1.40

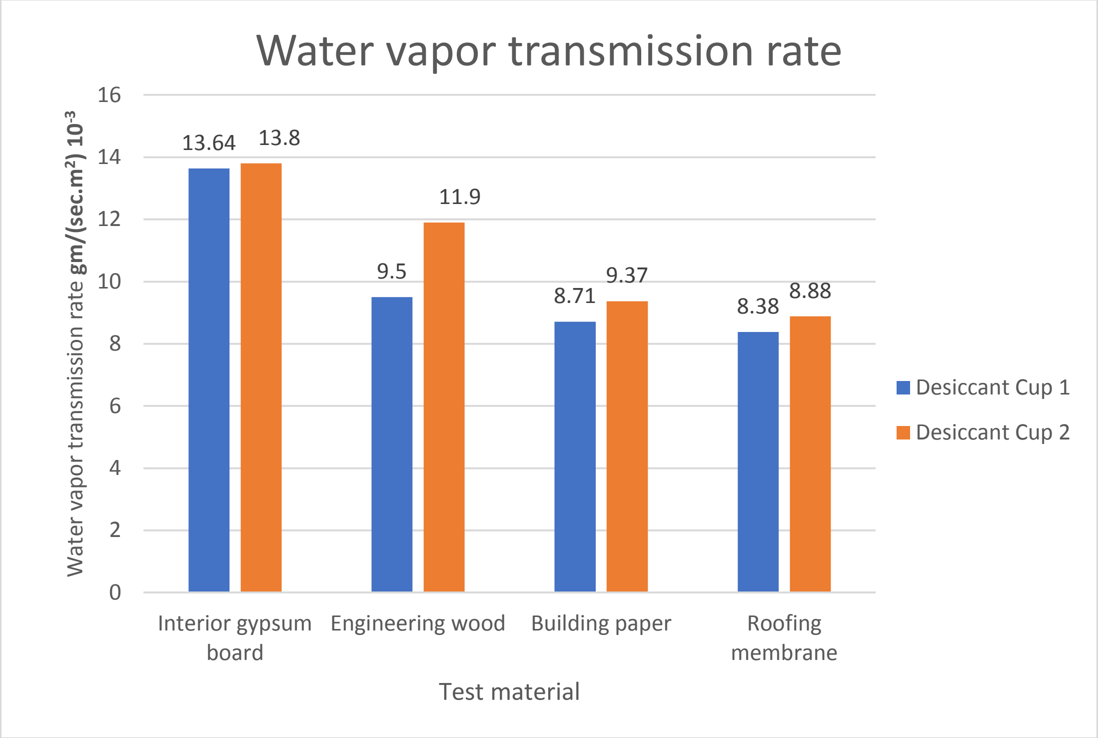

Figure 11 - Comparison of WVT of building materials at 50±2 °C (Modified cup 1 and modified cup 2)

The above tables and graphs show the effect of the temperature on the water vapor transmission properties. It is quite evident from the results that, in general, the WVT rate increases with increase in temperature. The observations clearly indicate that the modified cup is simple and versatile technique to determine the effect of temperature on the water vapor transmission properties on the building materials.

7.4 Comparison of water vapor permeability of building materials at 3±1ºC, 22±2ºC and 50±2ºC

The effect of temperature on water vapor permeability of the building material are shown in Figures 12 and 13. The results clearly indicate that there is no consistent pattern of change in water vapor permeability of building materials between the temperature range 3 ºC to 50 ºC. These observations are similar to the information available in published literatues [1,8-10,14-15].

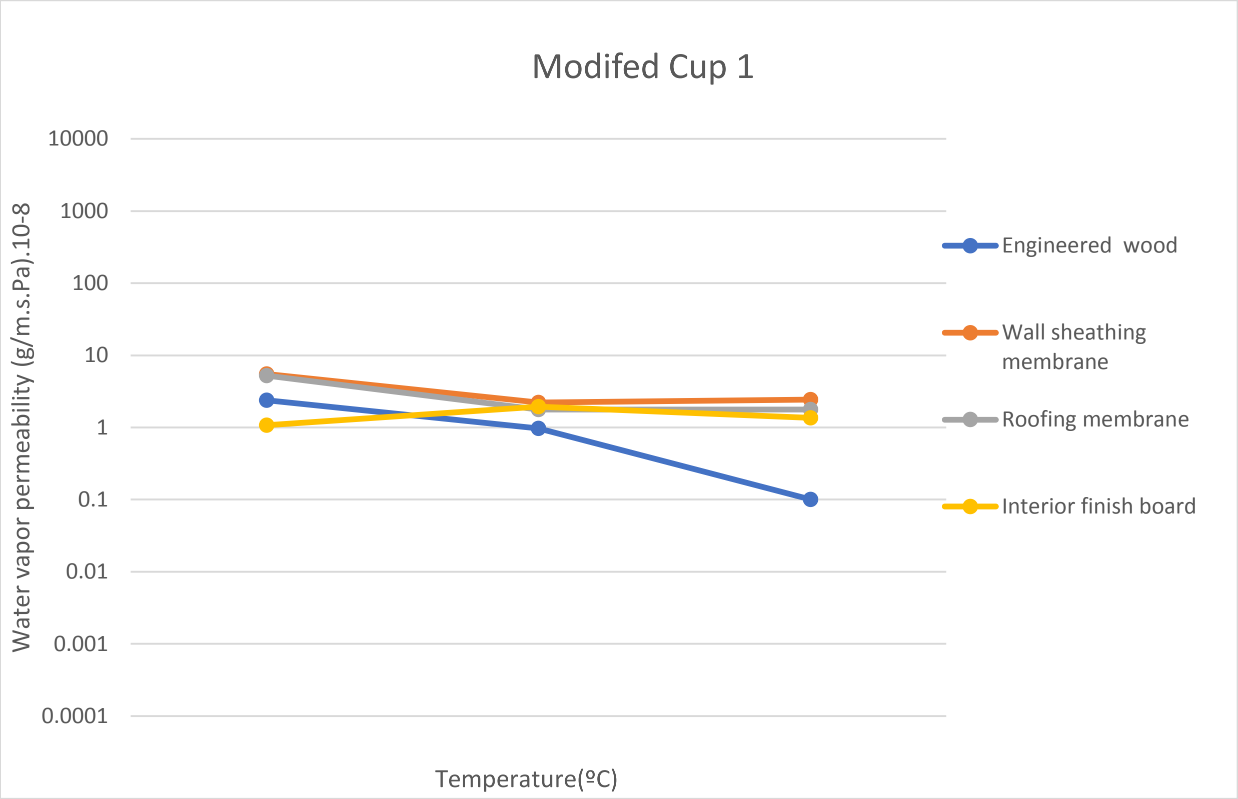

Figure 12 - Comparison of water vapor permeability of building materials at 3±1°C, 22±2°C and 50±2°C (modified cup 1)

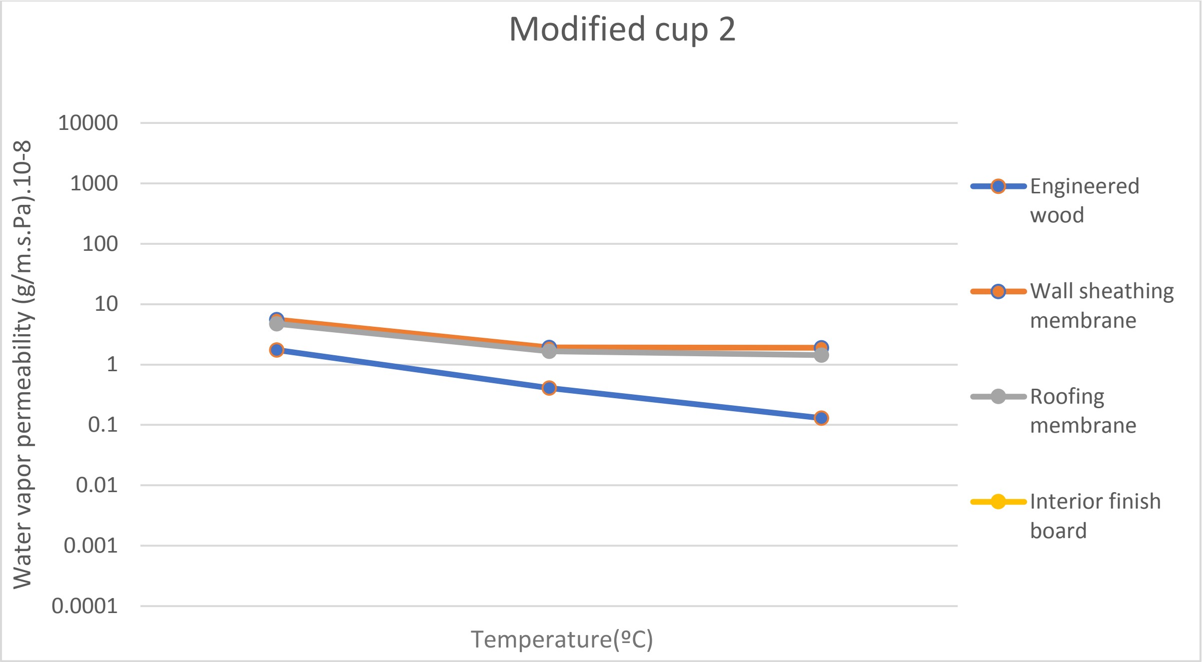

Figure 13 - Comparison of water vapor permeability of building materials at 3±1°C, 22±2°C and 50±2°C (modified cup 2).

8. Conclusion

This report presents the results from laboratory experiments which investigate water vapor transmission properties of building materials at three different temperatures (between 3°C and 50°C). The study examines the influence of temperature on the rate of water vapor transmission, water vapor permeance, and water vapor permeability of four different building materials (interior finish board, engineered wood, wall sheathing membrane and roofing membrane). As expected, in general, the water vapour transmission rate increased significantly with increase in temperature. From the test results obtained in this project the water vapor permeability values at 50% mean relative humidity seem to have no consistent relationship with the temperature at which the tests were conducted.

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Appendix

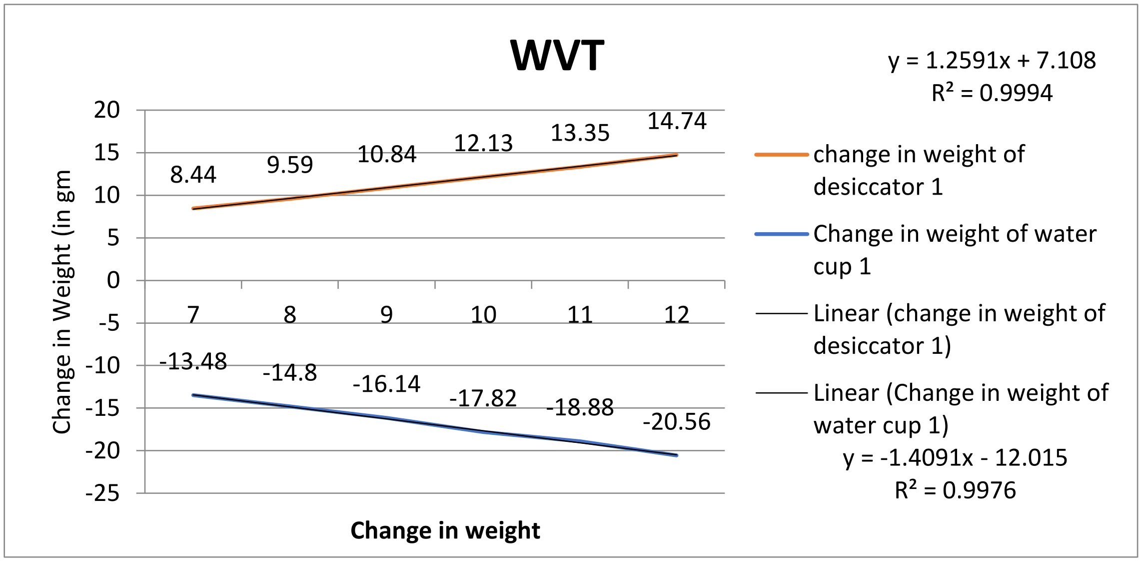


Figure 14 – Engineering wood at room temperature modified cup 1

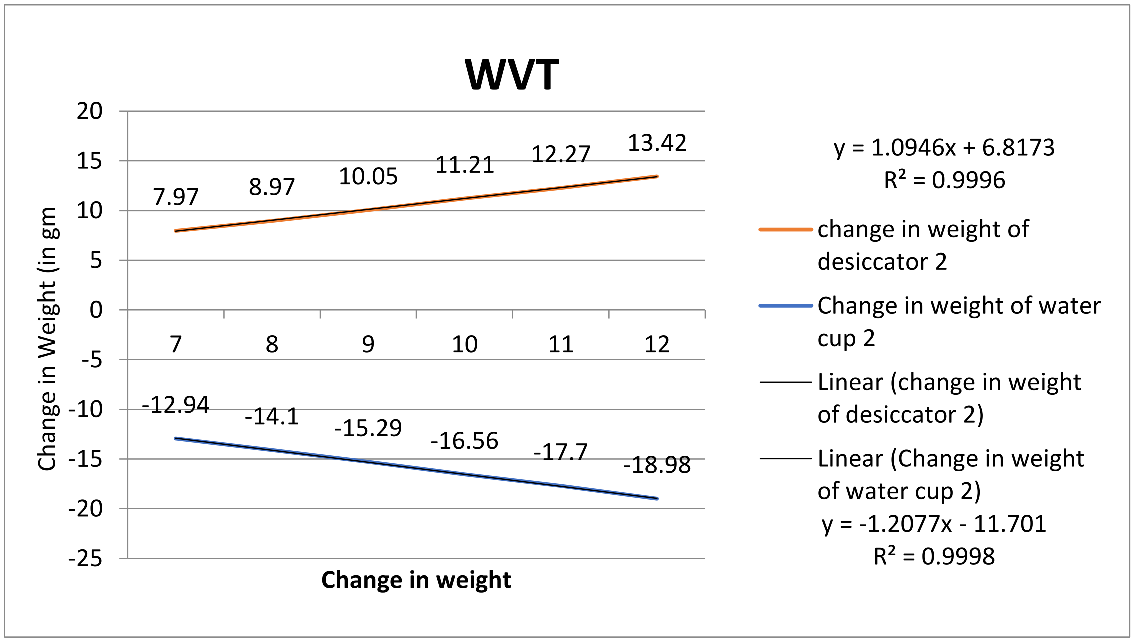


Figure 15 - Engineering wood at room temperature modified cup 2

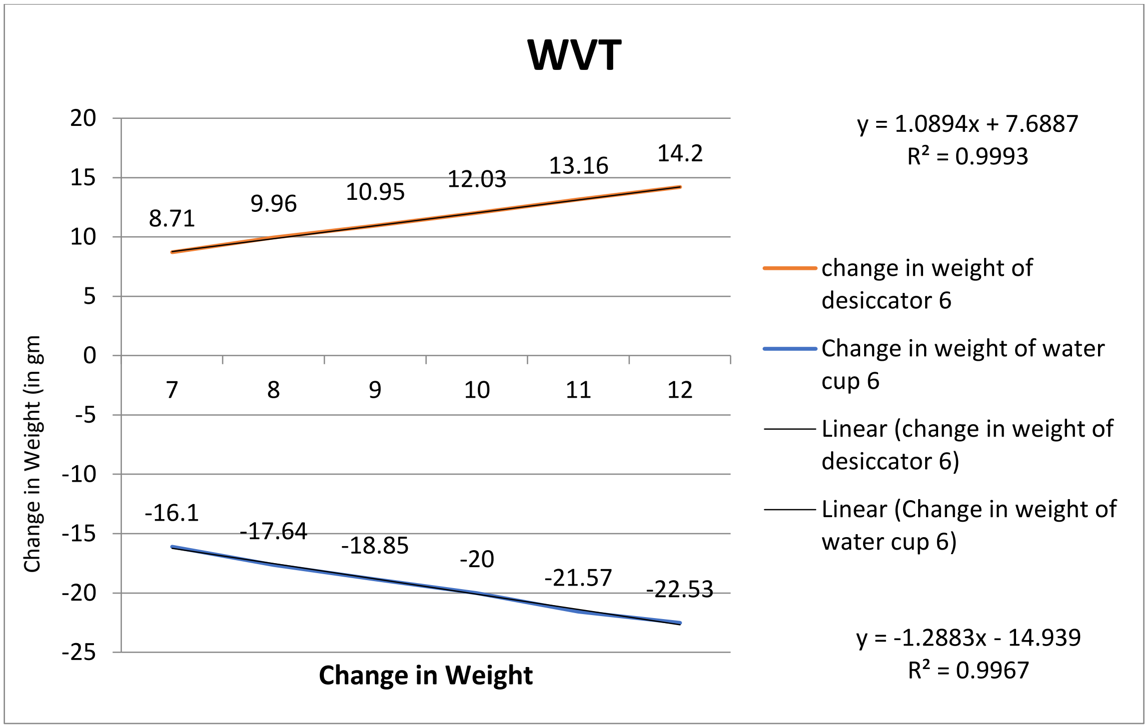


Figure 16 – Engineering wood at low temperature modified cup 1

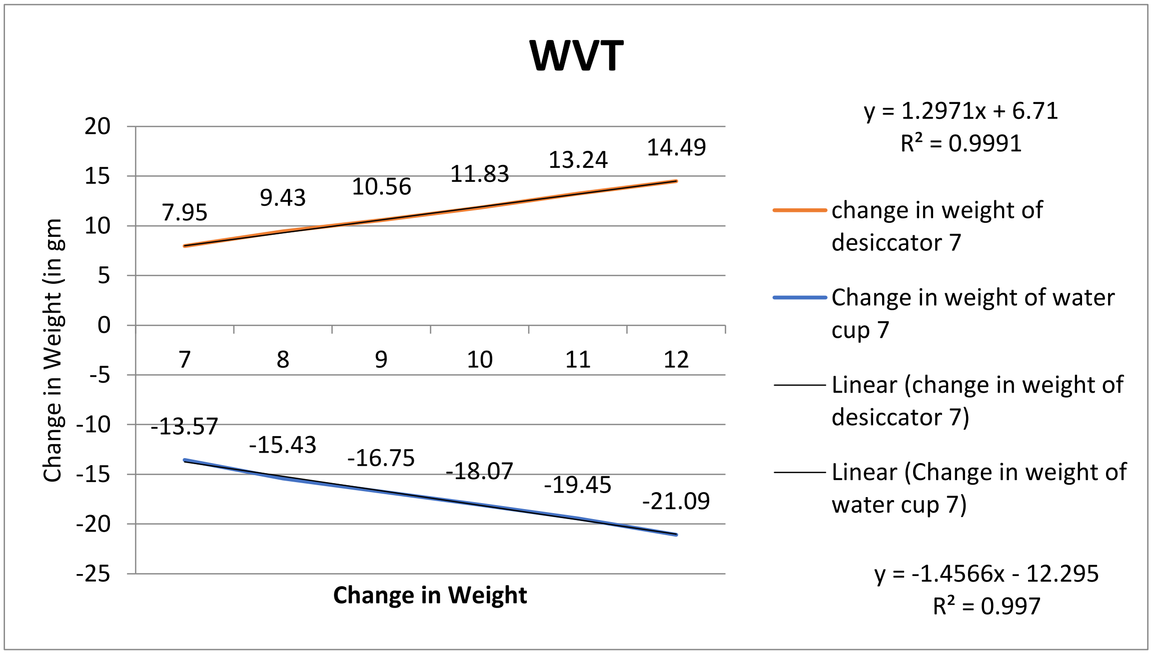


Figure 17 – Engineering wood at low temperature modified cup 2

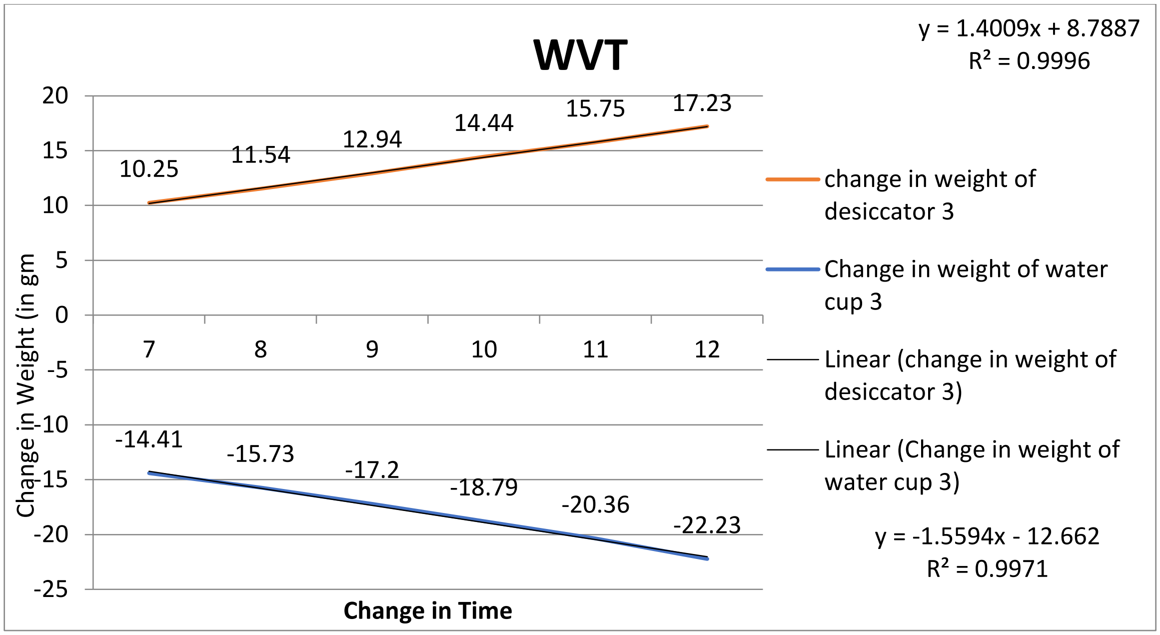


Figure 18 – Engineering wood at high temperature modified cup 1

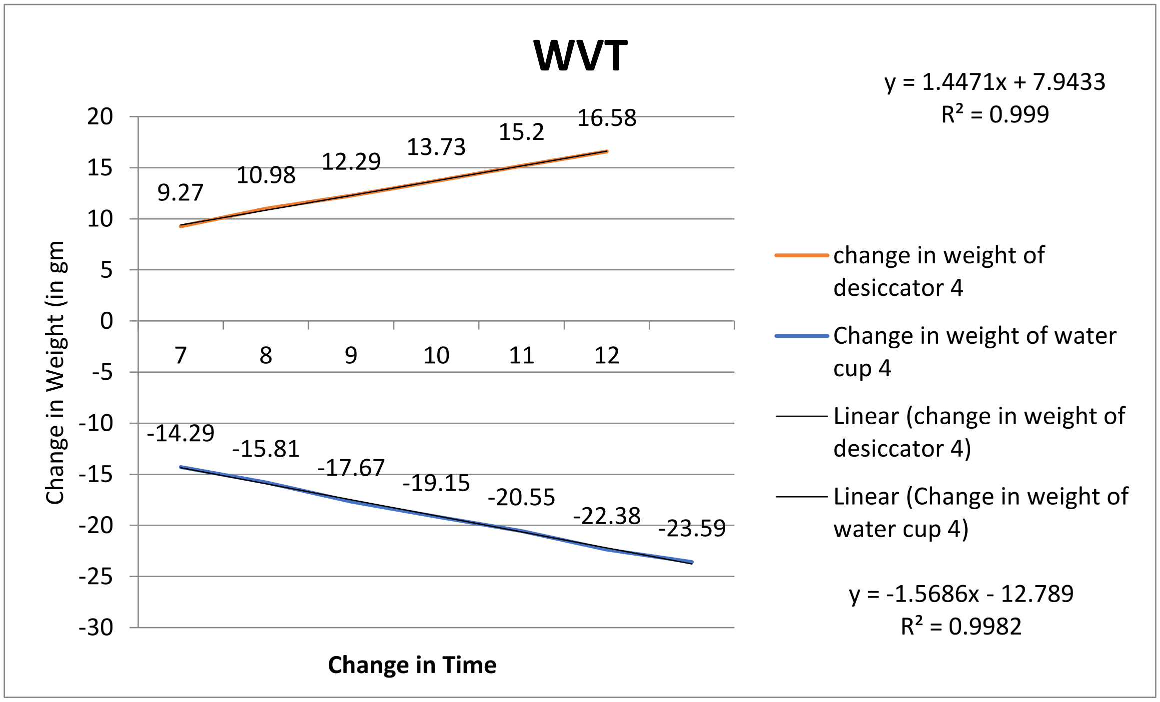


Figure 19 – Engineering wood at high temperature modified cup 2

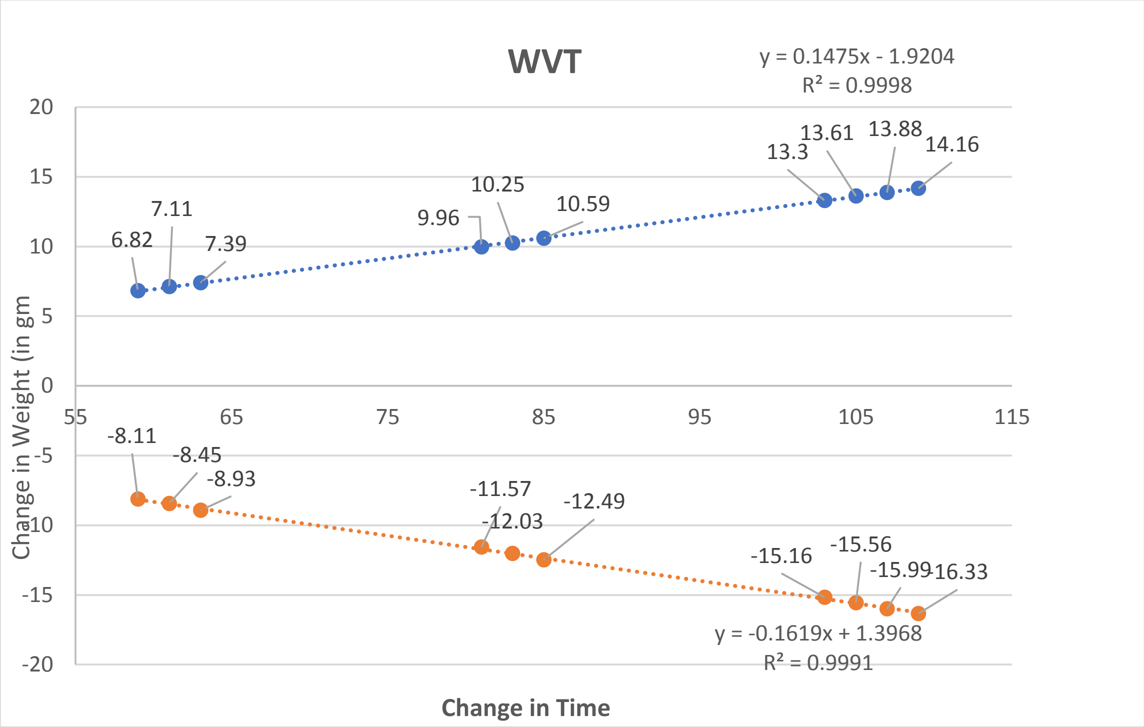


Figure 20 - Building paper at room temperature modified cup 1

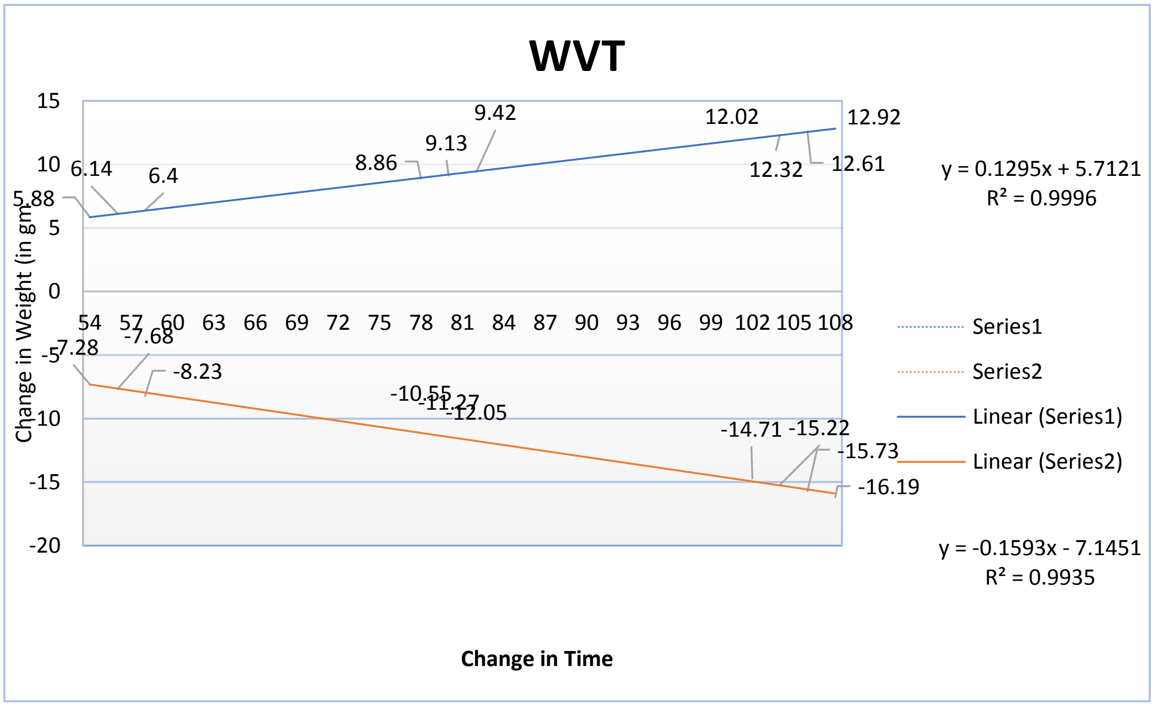


Figure 21 - Building paper at room temperature modified cup 2

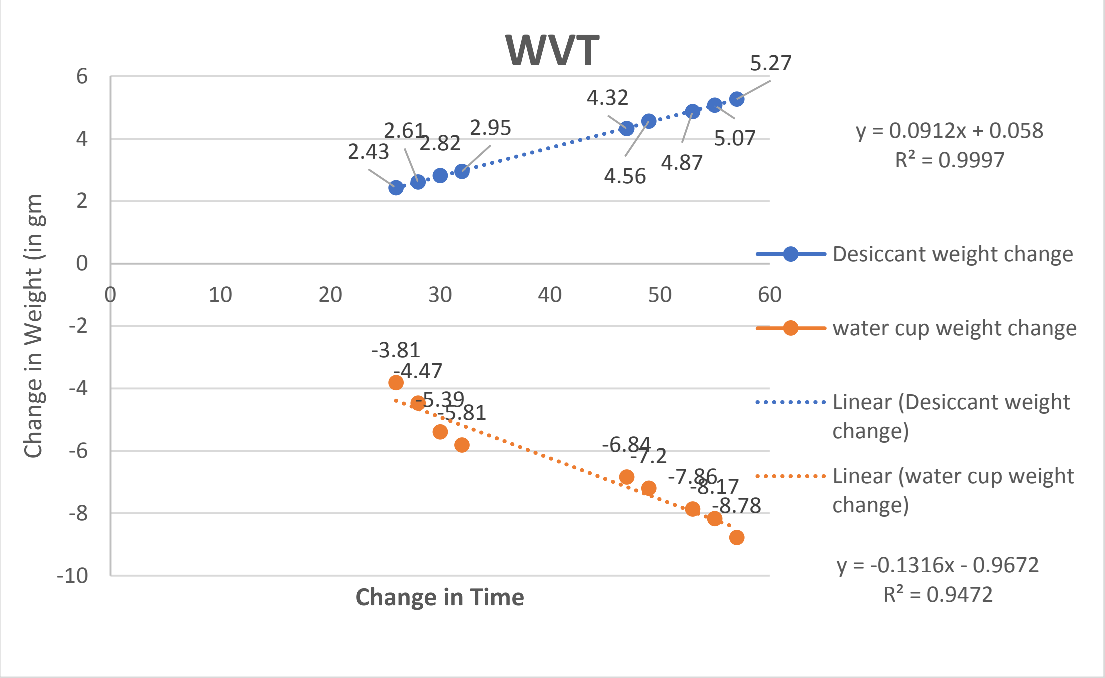
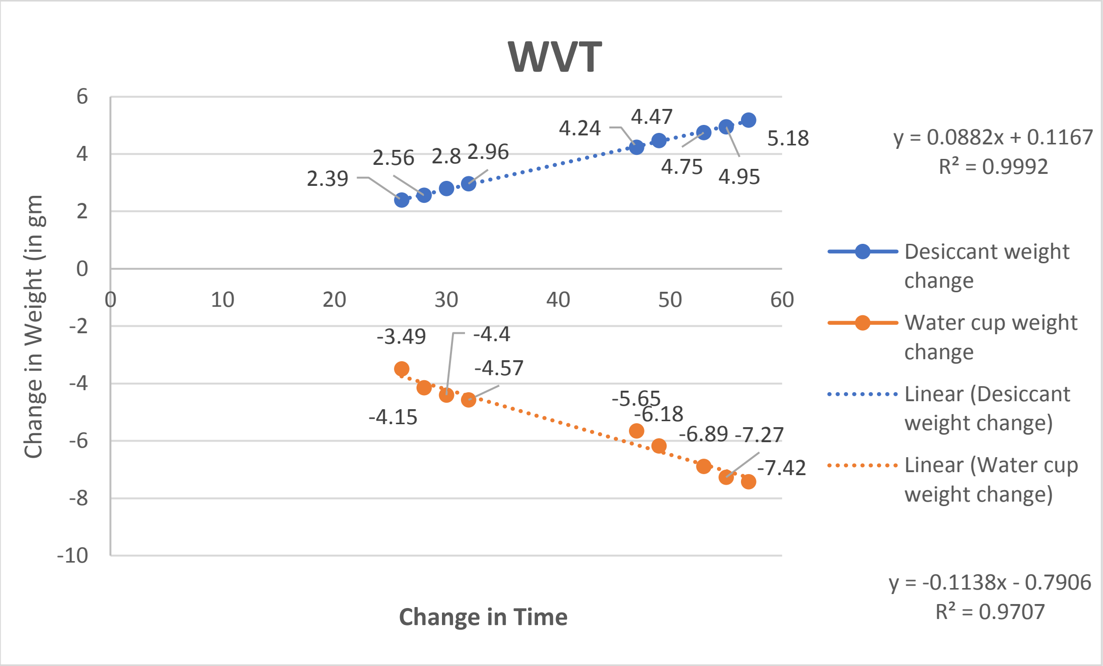


Figure 22 - Building paper at low temperature modified cup 1



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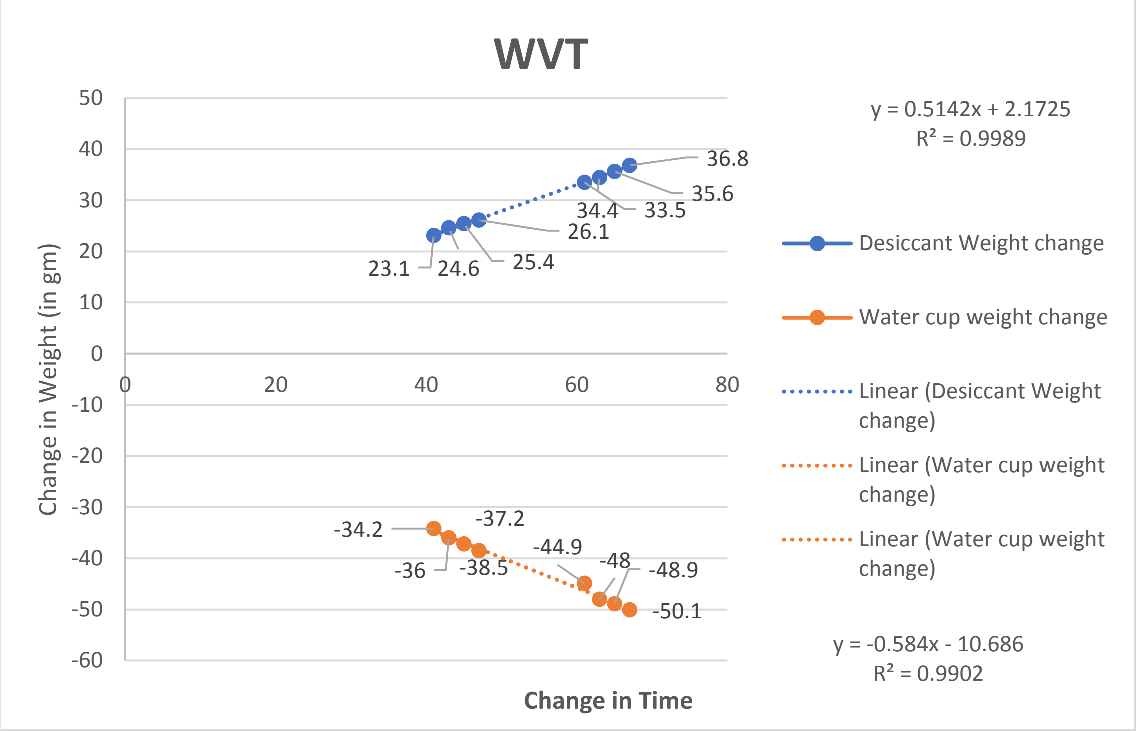


Figure 24 - Building paper at high temperature modified cup 1

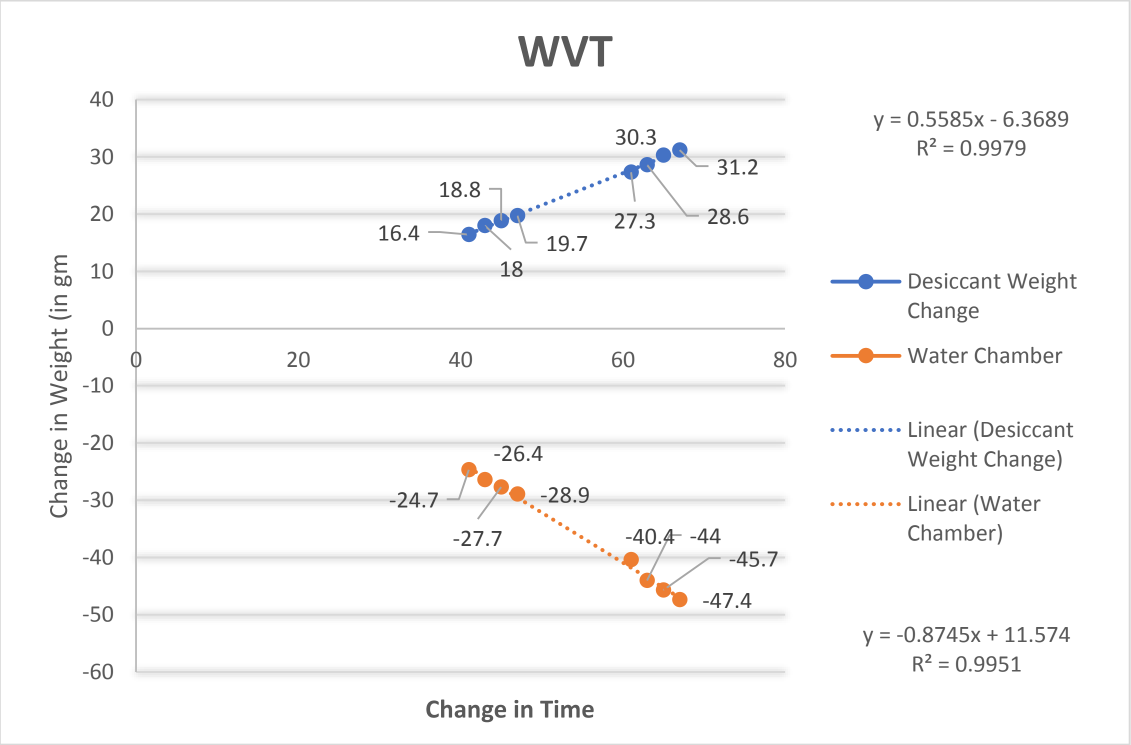


Figure 25 - Building paper at high temperature modified cup 2

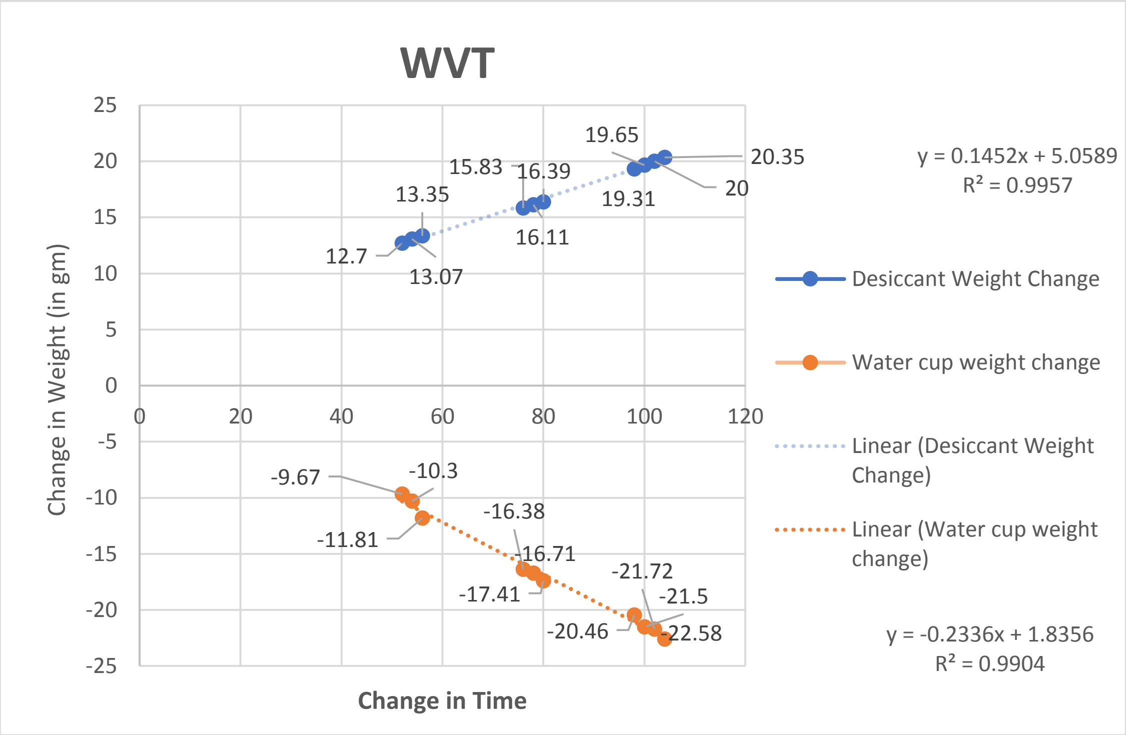


Figure 26 – Roofing membrane at room temperature modified cup 1

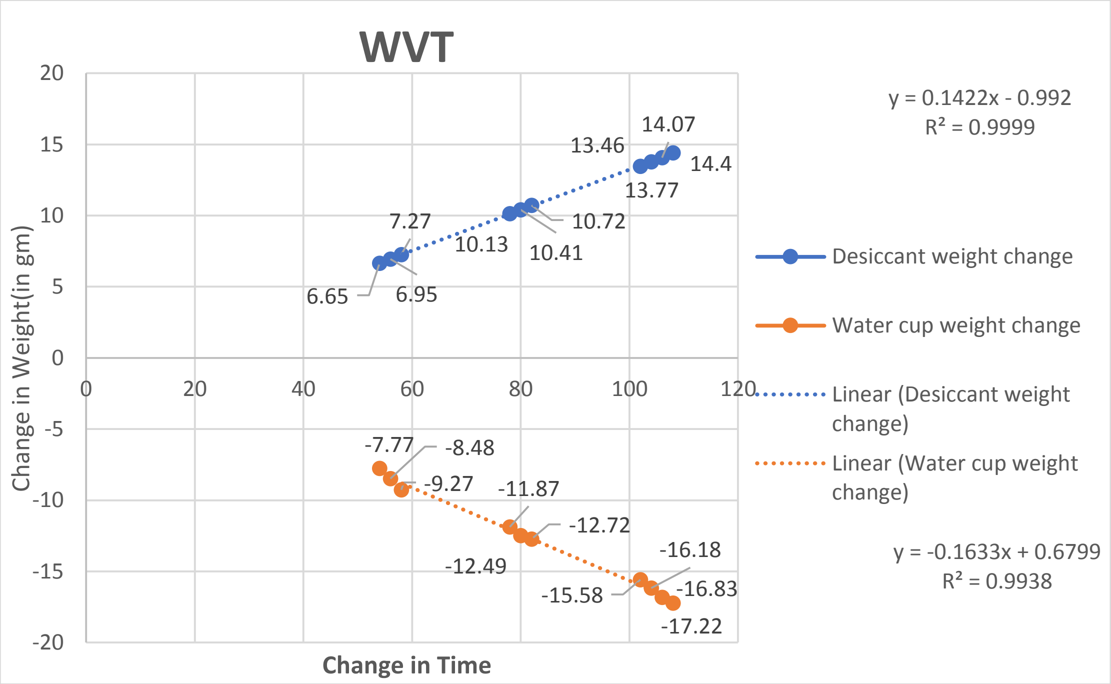


Figure 27 – Roofing membrane at room temperature modified cup 2

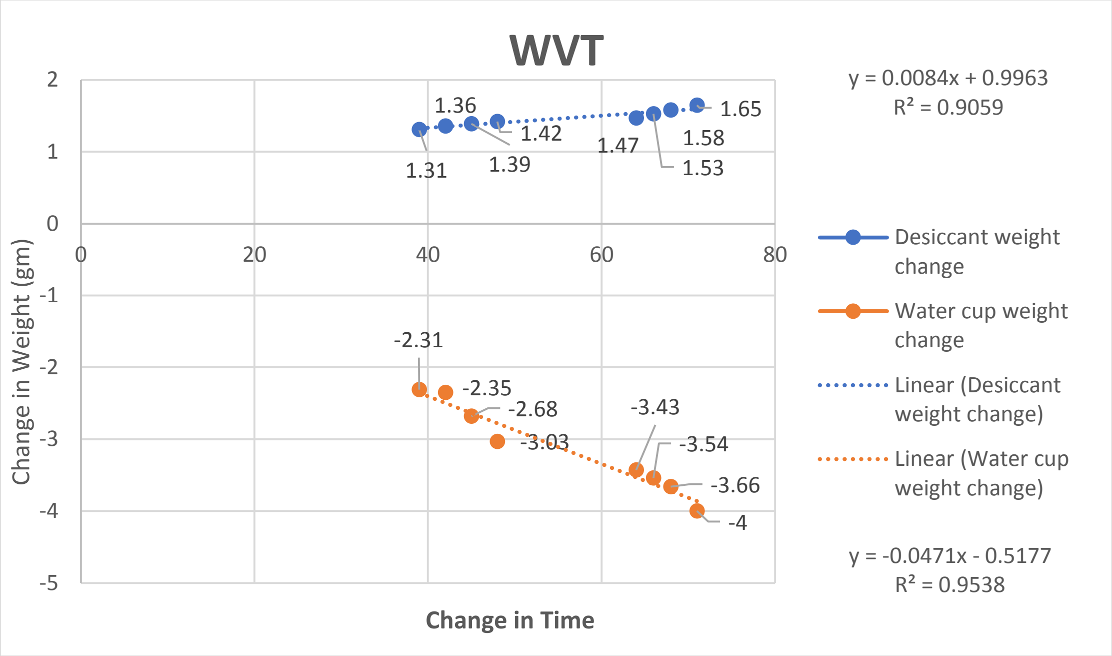
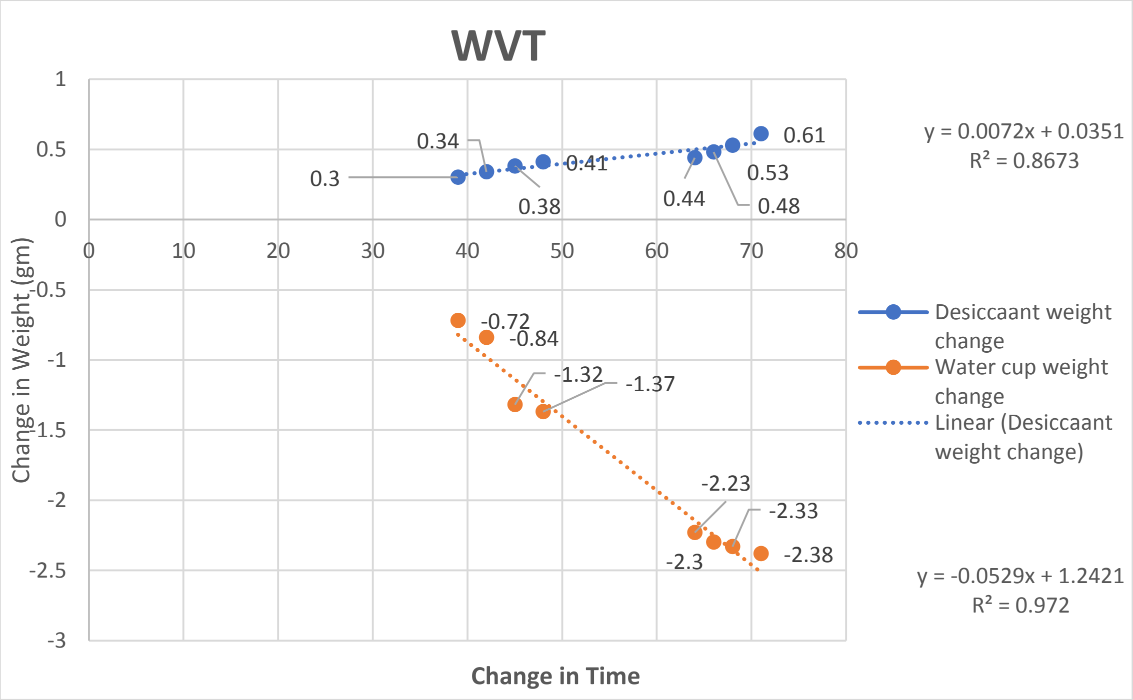


Figure 28 – Roofing membrane at low-temperature modified cup 1



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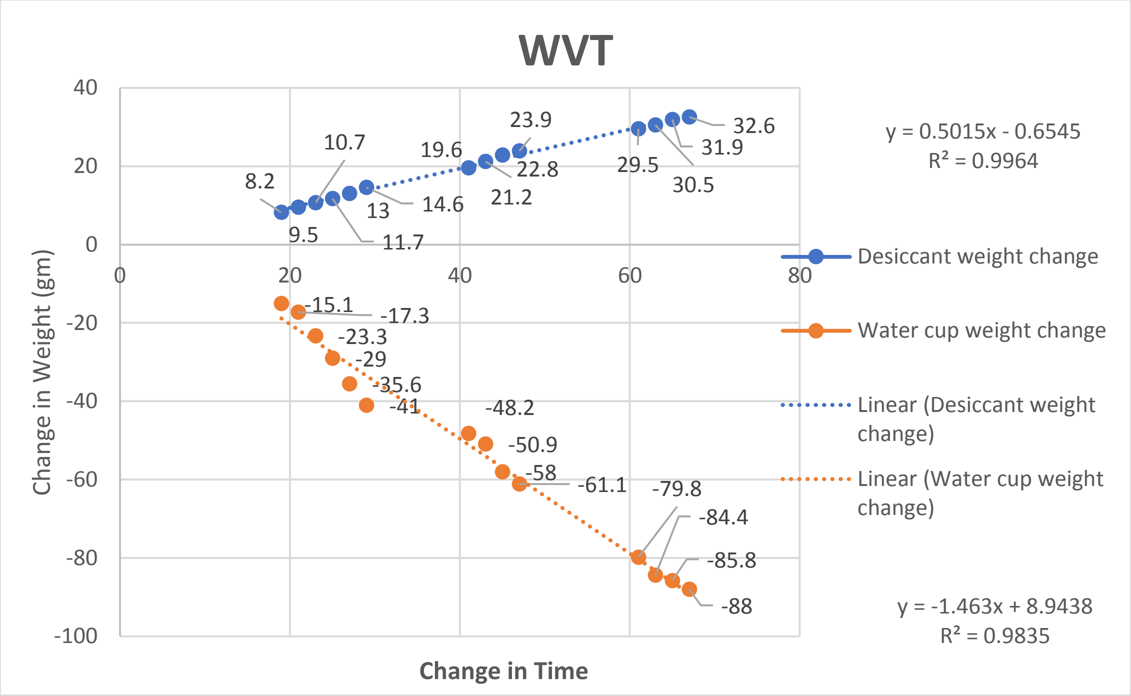

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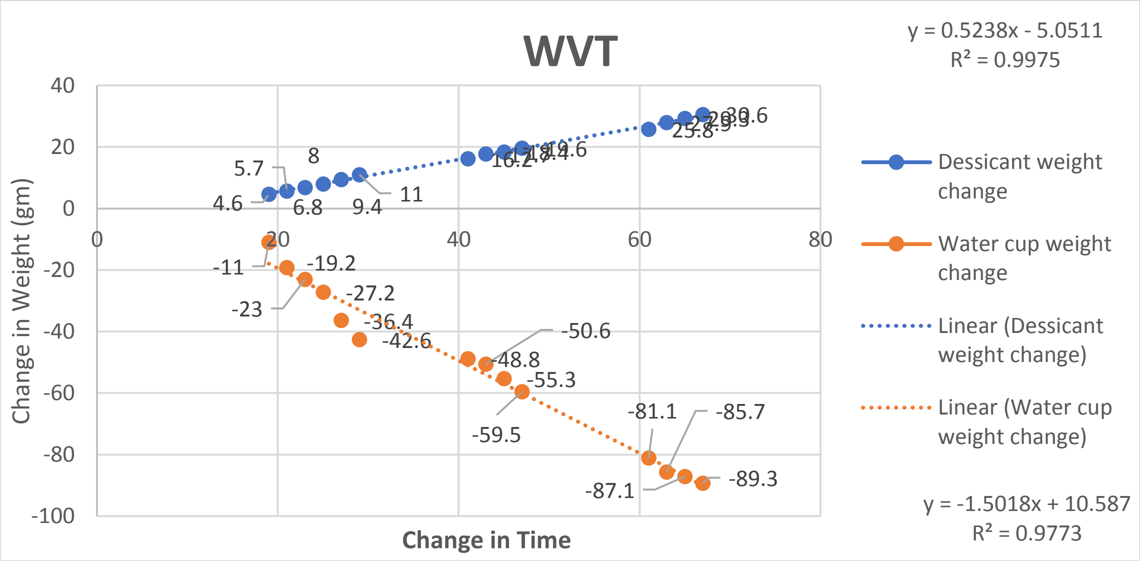

Figure 31 – Roofing membrane at high-temperature modified cup 2

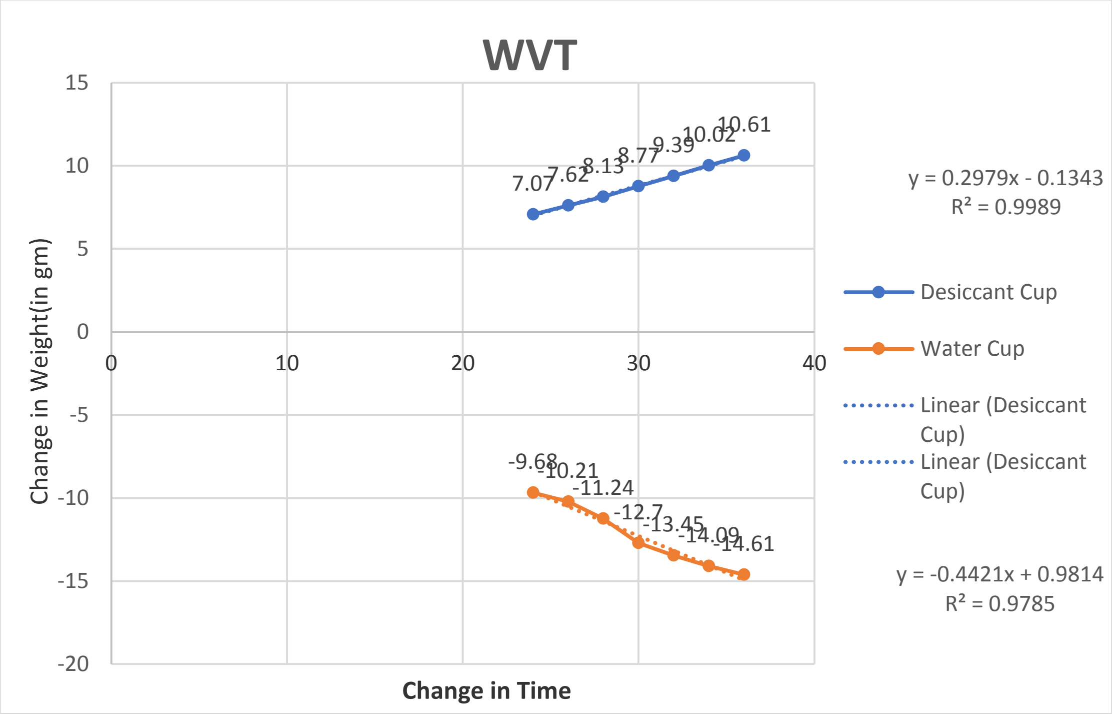

Figure 32 – Interior gypsum board at room temperature modified cup 1

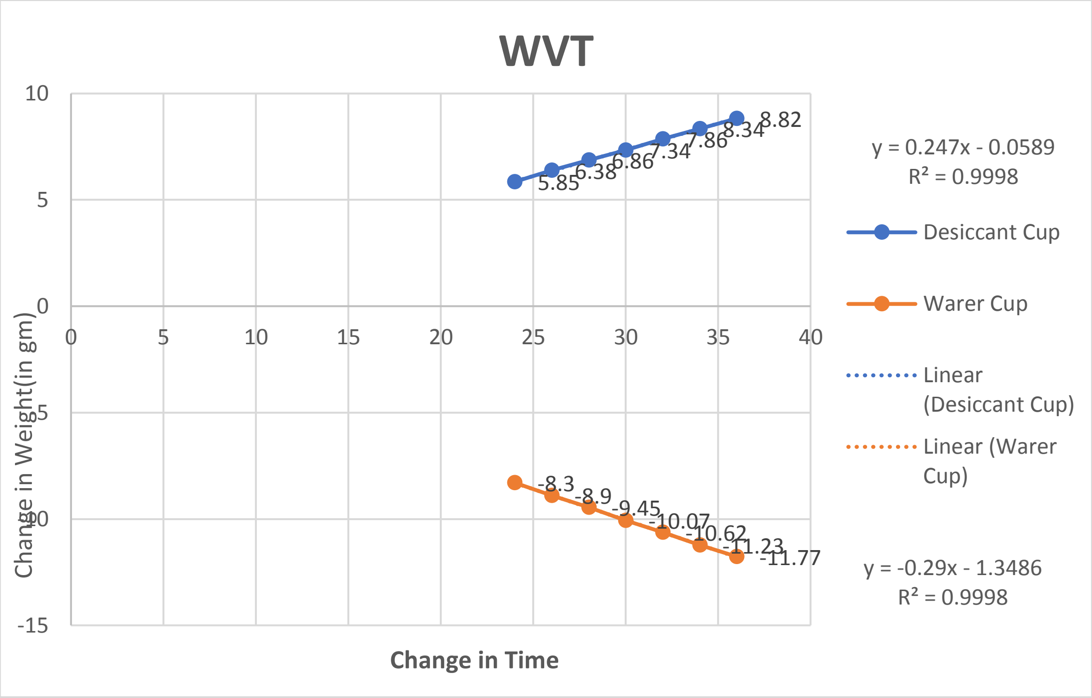

Figure 33 – Interior gypsum board at room temperature modified cup 2

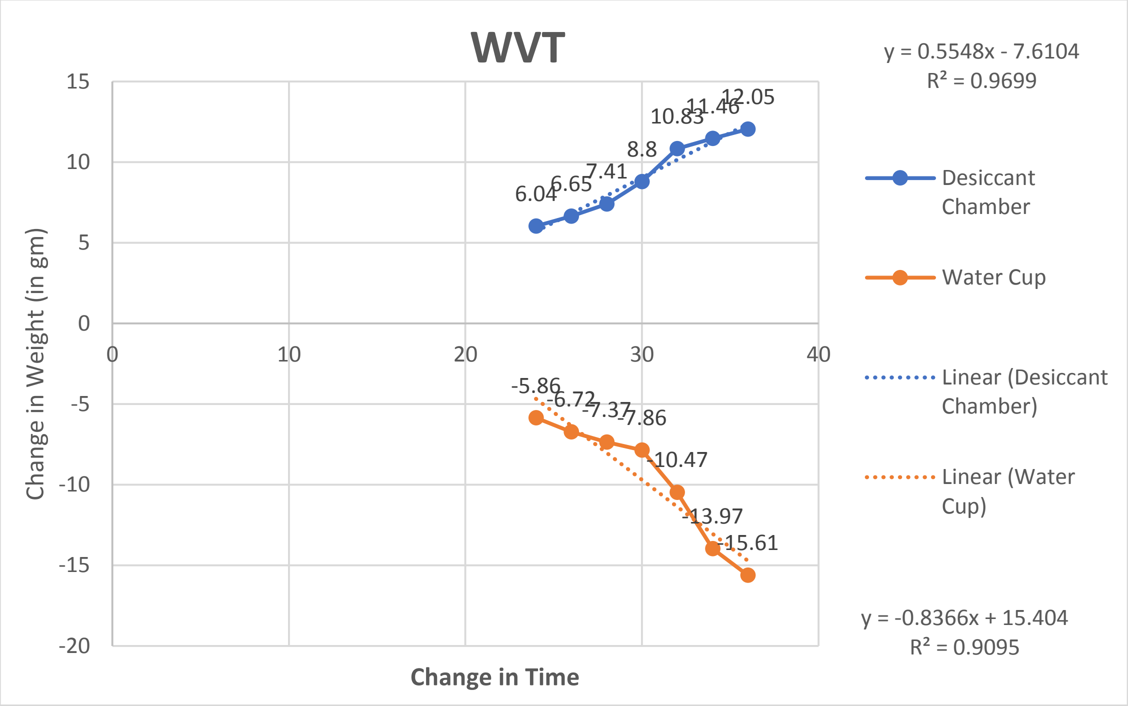

Figure 34 – Interior gypsum board at low-temperature modified cup 1

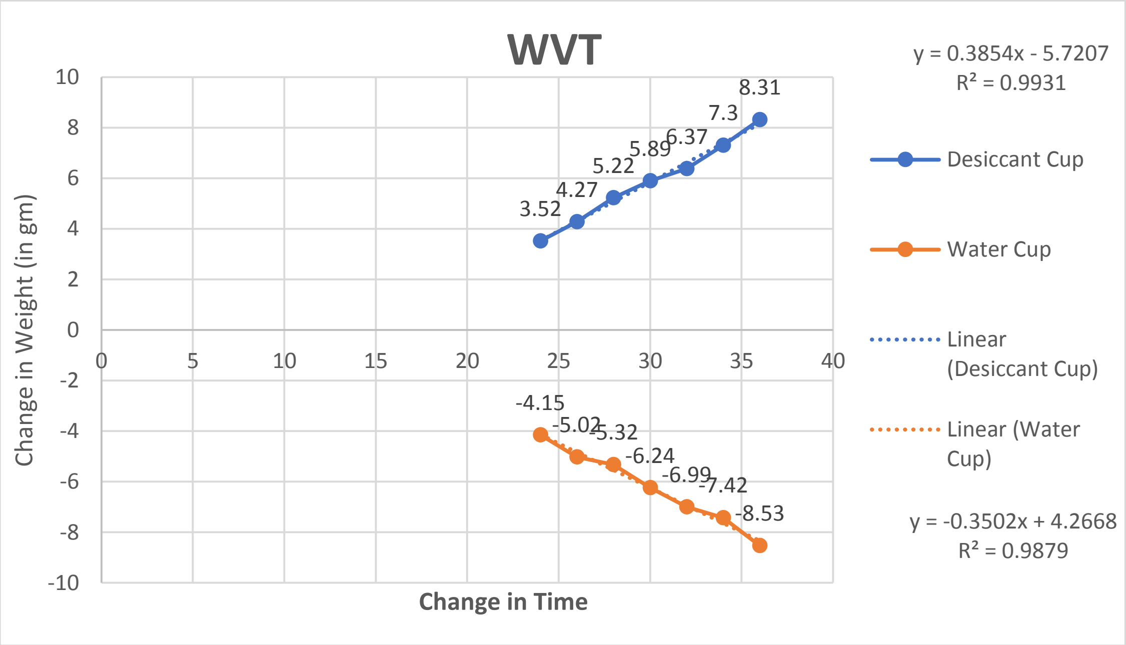

Figure 35 – Interior gypsum board at low-temperature modified cup 2

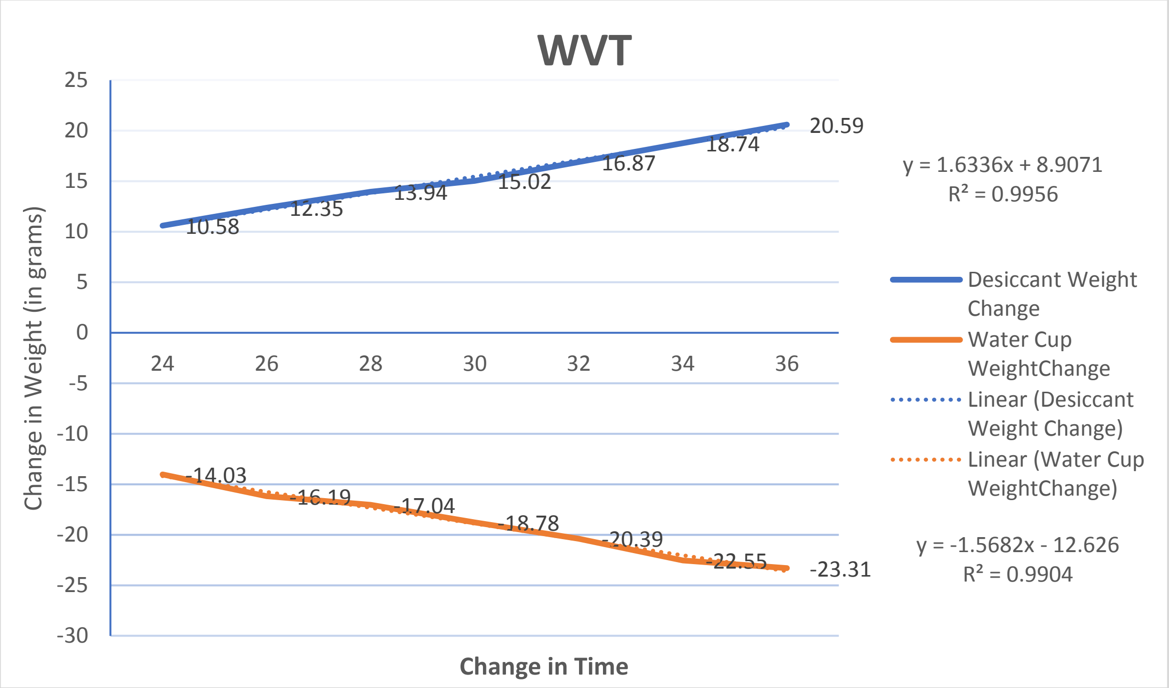

Figure 36 – Interior gypsum board at high-temperature modified cup 1

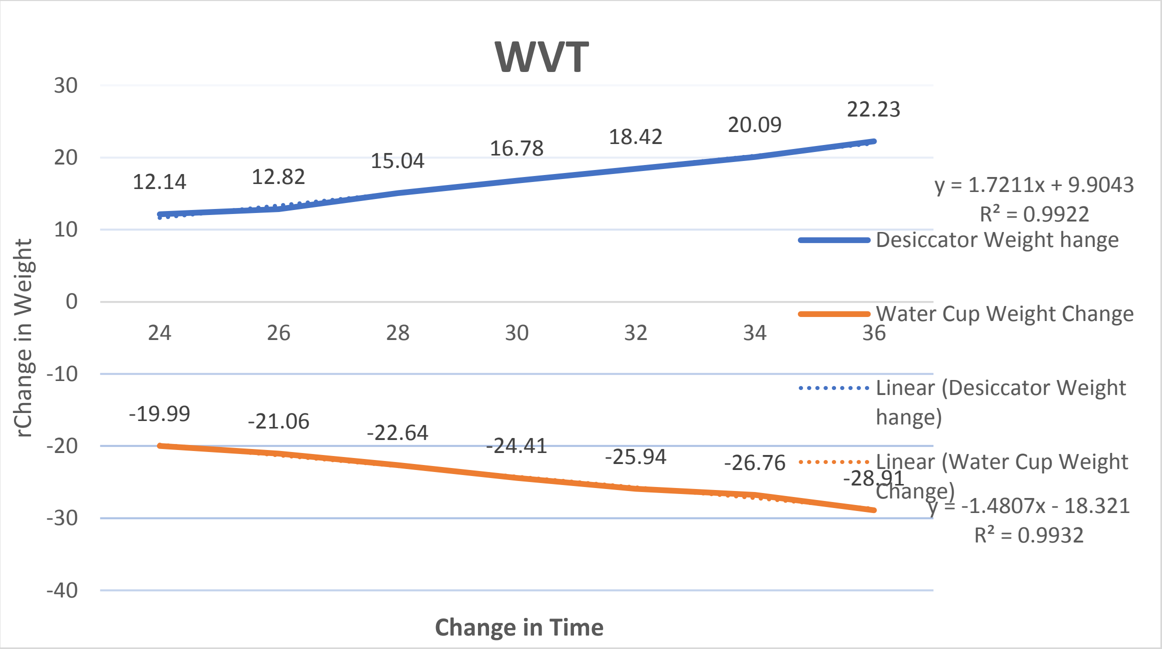

Figure 37 – Interior gypsum board at high-temperature modified cup 2