THE EFFECT OF DIFFERENT MIX PROPORTIONS ON THE HYGROTHERMAL PERFORMANCE OF HEMPCRETE IN THE CANADIAN CONTEXT

By

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Abstract

Hempcrete is a light composite bio-based envelope plus insulation material with lime as binding agent and hemp as a renewable raw material from agriculture. The main qualities of hempcrete are hygrothermal behavior and low environmental impact. There is currently lack of clear cross-industry standards for hempcrete; however, extensive research, laboratory experiments and literature reviews are ongoing. The primary aim of this study was to understand the impact of different mixes on the performance of hempcrete and to establish hygrothermal behavior of a hempcrete wall in the Canadian context (by measuring dry density and some other hygroscopic parameters for 3 different mixes) as well as to define the required minimum thickness for a code compliant wall (as per OBC requirements) based on the most reliable reference R values. Based on the material values acquired from the tests and references, simulations for 2 types of wall assemblies and series of sensitivity analysis were carried out in WUFI software. Finally, further research on hygrothermal performance of hempcrete wall (using Canada grown hemp) was recommended to carry out by measuring thermal conductivity in various mean temperatures.

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To all of you whose names were inadvertently omitted, my sincere apology.

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Abbreviations

ACH	Air change per hour
AFUE	Annual fuel utilization efficiency
ASHRAE	American Society of Heating, Refrigeration and Air Conditioning Engineers
ASTM	American Society for Testing and Materials
BRE	Building Research Establishment
CO2e	Equivalent Carbon dioxide
CSA	Canadian Standards Association
ENTPE	Ecole Nationale des travaux publiques de l'état (National School of Public Works of the State)
FTC	Federal Trade Commission
HAM	Heat, Air and Moisture
ISO	International Standards Organization (International Organization of Standardizations)
LCA	Life Cycle Assessment
MBV	Moisture buffer value
MC	Moisture Content
MRV	Moisture Retention Curve
NHL	Natural Hydraulic Lime
OBC	Ontario Building Code
pH	Potential of Hydrogen
RH	Relative Humidity
RVE	Representative Volume Element
SA	Surface Area
WC	Water Content
WME	Wood Moisture Equivalent

WUFI	Wärme und Feuchtetransport Instationär (Dynamic software to simulate heat and mass transfer in building components)

Symbols

[K] θ, T	Temperature
[%] ϕ, RH	Relative humidity
[m3], [cm3] RVE	Representative volume element
[kg] m	Mass
[m3] V	Bulk volume
[m] d	Thickness
[kg/m3] ρ	Density of material
[%vol], [m3/m3] Φ	Total porosity
[kg/m3], [%mass] w	Water content
[kg/m3], [%mass] w_f	Water content at free saturation
[kg/m3], [%mass] w_{max}	Maximal water content
[kg/m3], [%mass] $WC_{80\% Equiv}$	WC at 80% RH
[kg/m3%HR-1], [%mass.%/HR-1] ξ_ϕ	Specific hygric capacity
[Kg/msPa] δ	Vapor permeability
[Kg/msPa] δ_a	Vapor permeability of air
[-] μ_0	Dry vapour diffusion resistance factor
[J/kgK] c_0	Dry Thermal capacity
[W/mK] k_0	Dry Thermal conductivity
[W/m2K] h_e	Heat transfer coefficient of outside surface
[W/m2K] h_i	Heat transfer coefficient of inside surface
[-] a_s	Short-wave absorptivity
[-] a_r	Rain absorptivity
[W/m2K] U	Thermal transfer coefficient, U-value
[m2K/W] R	Thermal resistance of the component, R-value

[m] Sd	Vapor diffusion thickness
[W/m2]	Heat flow through inside/outside surface of component
[%]	Dampening
[g/m2.%HR-1] MBV	Moisture Buffer Value
Δ	Difference
[m2/s] α	Thermal Diffusivity
[J/m2 Ks$^{-1/2}$] Eff	Thermal Effusivity
[kg/m2 s$^{-1/2}$] A-value	Liquid absorption coefficient
[m/s] v_{wind}	Wind Speed
[%/%mass] b	Thermal Conductivity Supplement
[kg/s$^{1/2}$] σ	Initial slope

1.0 Introduction

1.1 Background

Hempcrete is a bio-aggregate- based natural (low-impact) envelope and an insulation system. It is a composite material composed of hemp shiv (hurd), lime binder and water. Hemp walls can have several distinct advantages including: energy efficient performance, achievable OBC standard, excellent level of airtightness and low thermal bridging, recyclable and produced using renewable sources, high moisture buffering, good performance fire resistance, high acoustic performance, high durability and high carbon sequestration (Alembic Studio, LLC 2013). Its thermal properties are dependent on the materials contributed, mix proportions, amount of water used, the degree of porosity and the final density. Hempcrete has a conductivity of 0.076 - 0.11 W/mK when mixed with a mild to moderate hydraulic lime consisting of ~85% hydrated lime and ~15% clay or pozzolans (Rhydwen, 2006). It is noticed that generally R 2-2.5/inch is targeted for hempcrete and 250-300mm thick wall is considered to be ideal (Magwood, 2013; Stanwix & Sparrow, 2014; Bevan & Woolley, 2008; Alembic Studio, LLC, 2013). Moreover, residential hemp construction projects are permissible under Section 9 of the Ontario Building Code as alternative solutions (Oliver, as cited in Kenter, 2015). Hempcrete can be produced by spraying, moulding and precasting and can be primarily used for wall, floor and roof insulation. Cast-in-situ is the preferred form because of the low-tech nature of the construction method and low embodied carbon (Stanwix & Sparrow, 2014).

Regardless of its benefits, hempcrete still has not gained momentum in application in Canada although Canada produces ample quantities of hemp (Canadian Hemp Trade Alliance, 2015; Endeavour Centre, ON). However, in Europe, hempcrete technologies are more commonly used since the early 1990’s (Rhydwen, 2006). By exploring previous researches and literatures, information on hempcrete in Europian context can be acquired, but to know the properties and hygrothermal performance of hempcrete in the Canadian context, this research “The effect of different mix proportions on the hygrothermal performance of hempcrete in the Canadian context” was conducted.

1.2 Research Objectives

The primary objectives of this study were; to obtain test values for different parameters for 3 mixes of hempcrete (hemp to binder ratio - 1:1, 1:1.5 and 1:2) using locally grown hemp; to understand the impact of different mixes on the performance of hempcrete; to define the required thicknesses of wall (above grade) to meet the prevailing OBC requirements (R value) and to establish the hygrothermal behavior of hempcrete wall in the context of Canada. The study was centered in answering the following questions:

1. What will be the impact of different mixes on the performance of hempcrete in Canadian context?

2. (a) What will be the minimum thickness of hempcrete wall required to meet the prevailing OBC requirements for thermal performance (based on the most reliable reference R values)?

   (b) What will be the hygrothermal behavior of hempcrete wall while modelling in WUFI by using partial lab tested material values and partial best appropriate reference values found from the reliable literatures?

The aim of this paper was to provide a more reliable and consistent source of information on hempcrete in the Canadian context through laboratory tests, literature review and WUFI simulations. In order to meet those objectives, laboratory experiments such as dry density (ρ_0) through oven drying, porosity (Φ), maximum water content (W_{max}) and free water saturation (W_f) through 5 hour boiling test and 48 hours cold water submersion test (according to ASTM C67) were executed. The saturation coefficient was determined based on ASTM C62. The entire test was performed after 26 days of drying. In addition, to understand the heat and moisture transfer behavior of hempcrete walls, one-dimensional hygrothermal analysis was conducted in WUFI for two types of wall assemblies [Assembly 1: Lime render+ Hempcrete wall + Lime plaster and Assembly 2: Wood Cladding (Spruce)+ Air Gap +Typar +Hempcrete wall+ Lime plaster] by getting additional appropriate reference materials input from relevant literatures. The reason behind choosing two assemblies was to compare the hygrothermal behavior of a wall with and without sun, rain and wind exposure. Similarly, the basic purpose of testing specific material properties was to increase the probable accuracy of the simulation as compared to utilizing all the literature inputs. A series of sensitivity analysis was also carried out to identify the impacts of such references. Finally, based on the analysis; findings, conclusion and recommendations were made.

2.0 Hempcrete

2.1 Background

Hempcrete is a bio-aggregate- based envelope and an insulation system; a bio-composite made of the inner woody core (Shiv or Hurd) of the hemp plant mixed with a lime-based binder. “Shiv” has a high silica content which allows it to bind well with lime (Alembic Studio, LLC, 2013). It doesn't slump, demonstrates more flexibility than concrete and cures within a few hours. While it doesn't have notable load-bearing capacity, this lightweight cementitious insulating material weighs only one-seventh the weight of concrete by volume and helps to strengthen the stud wall (Oliver, as cited in Kenter, 2015). Hemprcrete, with flexible hemp and rigid binder leads to a non-fragile elasto-plastic behavior. Hence, it is distinguished from other construction materials by a high deformability under stress, lack of fracturing and high ductility with absorbance of the strains after reaching the maximum mechanical strength (Arnaud & Amziane, 2013).

Hempcrete has low effusivity and high thermal inertia, so it does not take as long to heat and once heated will slowly release heat when the temperature drops (Evard, 2008). Being fully recyclable; any waste on-site can be re-used in the next mix. In this manner, the hempcrete can be easily broken down and re-used in a new build once the building is being demolished. As landfill, being a natural product, it will break down over the course of time and contribute lime and organic matter to the land (Hemp Edification, 2015). However, this porous, lightweight material is a good thermal insulator, although not an exceptional one (Arnaud & Amziane, 2013).

Particle size/ moisture content of the shiv, proportions of hemp to binder, mixing, placing and compaction are the significant variables in the thermal performance of hempcrete (Woolley, 2012).

2.2 History

Hempcrete is fundamentally a modern version of very old natural composite construction materials (Stanwix & Sparrow, 2014). It was confirmed by archaeologists that the hemp shiv was used in the construction of a bridge, in the 6th century AD, in southern France. However, the first modern use of hemp fiber composite construction was in France in 1990 for the renovation of historic timber-framed buildings, casting the hemp lime mixture around the timber frame (Bedlivá & Isaacs, 2014). Meanwhile, literature analysis in hempcrete started in 2002 and is still going on extensively (Evard, 2008).

2.3 Hemp and Binder

2.3.1 Hemp

Hemp (botanical name: Cannabis Sativa) shiv is a waste material from the agricultural production of hemp seeds for food and oil. The processing of hemp for hempcrete is mechanical, so no chemicals are needed for this product. General chopped hemp size used is 1.0-2.5 cm (Kennedy et al, 2002). Because of its highly porous structure and strong capillarity effects inside the tubes, hemp is able to absorb large amounts of water (up to 10 times its own weight) (Kennedy et al, 2002). Walker & Pavia (2012) states that hemp aggregate absorbs big quantities of water (325% of its own weight at 24 h), as a result it can hold mixing water that is required for hydration and carbonation (Walker and Pavia, 2014).

General properties of Hemp Fibers are: specific gravity (g/mm^3): 1.5, moisture absorption (%): 9.40±0.53, water absorption (%): 85–105, tensile strength (MPa): 900, modulus of elasticity (GPa): 34 (Li et al, 2006) and bulk density: about 115 kg/m3 (Arnaud & Gourlay, 2012). Chemical composition of hemp herd constitutes cellulose (50-60%), hemicellulose (15-20%), lignin (20-30%) and pectin (4-5%) (Tolkovsky, 2010).

2.3.2 Lime Binder

Basically two types of natural limes are used in hempcrete as binder (Stanwix & Sparrow, 2014):

1. Hydraulic lime $C_a(OH)_2$ (Hydrated Lime or Calcium Hydroxide + Calcium Silicate +Calcium Aluminates): Hydraulic or water exposure set (from hydration), fast set, high strength and low vapor permeability.
2. Hydrated (Air or putty) lime $C_a(OH)_2$ (Calcium Hydroxide): Air exposure set (from carbonation), slow set, low strength and high vapor permeability and hygroscopicity.

Pure hydraulic lime is said Natural Hydraulic Lime (NHL), whereas pozzolan added hydrated lime is called “Formulated Hydraulic Lime” (FL or HL). Formulated or proprietary hydraulic lime (Lhoist, Batchanvre, Vicat etc.) sets with the mixture of hydration and carbonation processes (Stanwix & Sparrow, 2014; Arnaud & Amziane, 2013). In hydrated lime, pH stays high for a long time and protects hemp hurds from mold growth or bacteria attack (Evard & Herde, 2010). However, binder can be locally formulated by mixing hydrated lime and pozzolan (Magwood, 2013). Meanwhile, Stanwix & Sparrow (2014) iterates hempcrete binders should have the properties of: strong hydraulic set to provide initial setting with enough strength to support the weight of drying wall, vapor permeability to allow water to continue to dry out of the hemp shiv after initial set and long term structural integrity to provide full setting over time.

However, Walker & Pavia (2014) reveals that binder doesn't influence the permeability, it is related only to micro porous; macro porosity is related with hemp shiv. Although binder doesn't play significant role in thermal conductivity or specific heat capacity, trend however suggests that increasing the binder's hydraulic content reduces thermal conductivity and increases heat capacity (Walker & Pavia, 2014). Lime wicks water away and protect the hemp particles from biological decay. Its high alkalinity, property of fire resistance, excellent insulation and airtightness reduce the energy consumption (Hemp Edification, 2015). Bulk Density of pre formulated binder is about 650 kg/m3 (Arnaud & Gourlay, 2012).

In summary, more binder means - more density, more compressive strength, more embodied carbon, low insulation performance (R-value), increased thermal mass, more flexural (bending) strength, likely to age better, more expensive, high Young's modulus and more hardness.

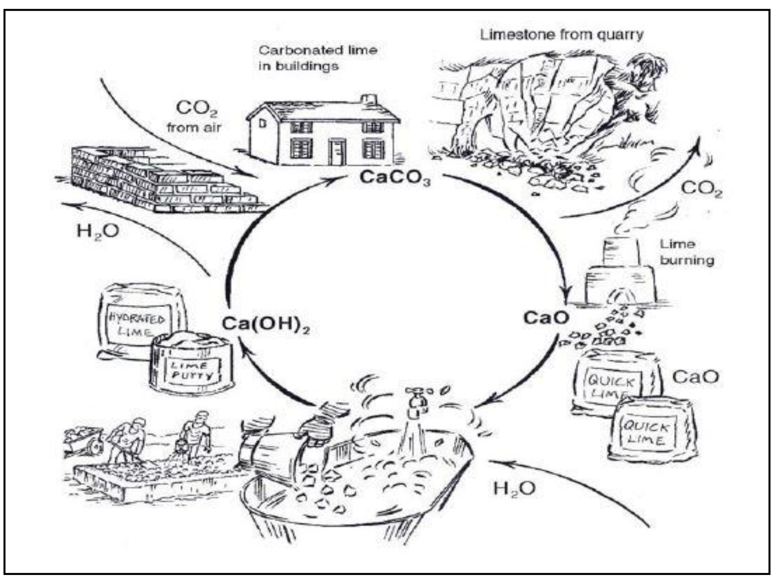


Figure 1: The Lime Cycles

(Dowd & Quinn, 2005)

As shown in Figure 1 above, $CaCo_3$ (limestone) goes the full circle from being broken down to carbonation when hempcrete is formed. As hempcrete hardens from carbonation, it will rigidify the hemp and build limestone (Hemp Edification, 2015).

2.4 Applications

Hempcrete, primarily is used in wall, floor (slab), render/plaster and roof (Figure 2). In roof, insulation is an important aspect so low density (light weight) is used, whereas for additional structural strength, high density hempcrete (low thermal insulation) is used in floor. Natural breathable finishing (lime render and plaster and mineral based paints) are commonly used in hempcrete wall. However, if cladding is used, breathable one with vented air gap in between the wall and cladding is better. Lime-hemp plasters and Hemp-fiber quilt insulation are other uses of hemp in construction industry (Stanwix & Sparrow, 2014).

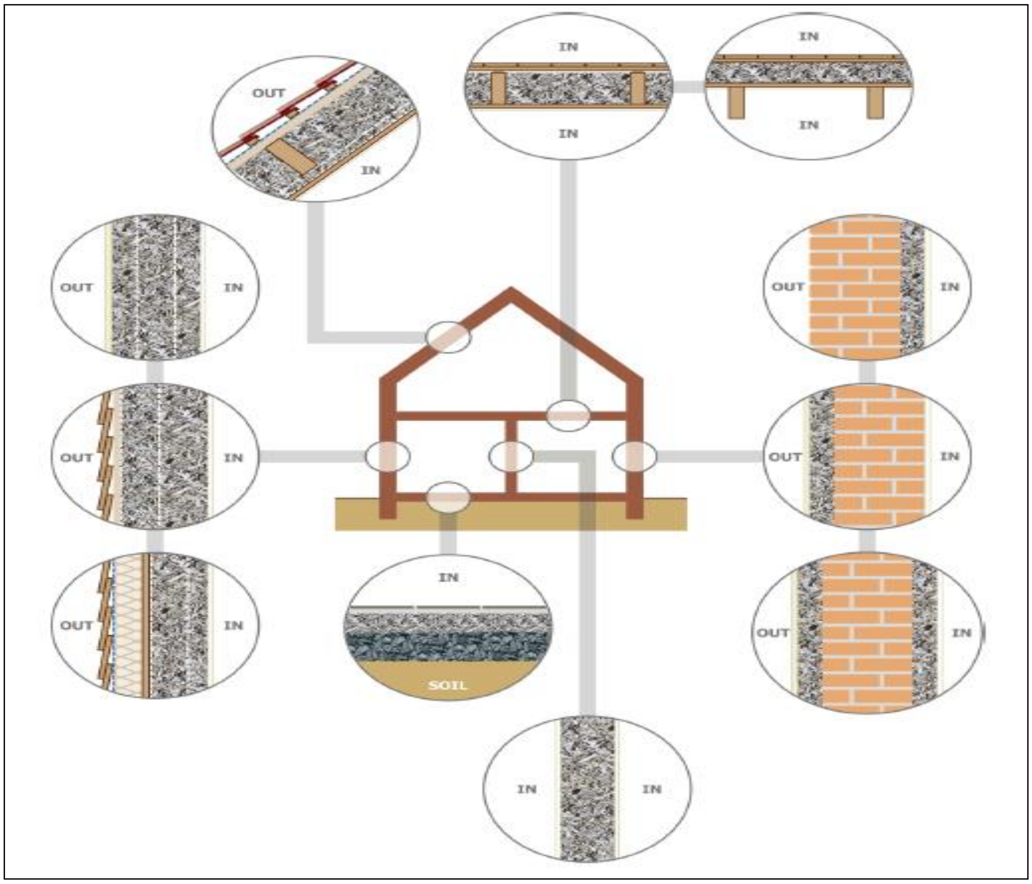


Figure 2: Numerous uses of hempcrete materials in buildings

(Evard, 2008)

2.5 Methods of Use

Hempcrete is usually used in a composite (timber frame) structure (with single or double studs placed centrally or closer to either the inner or outer wall face, as per finishing requirements) because of low compressive strength (Woolley, 2012; Stanwix & Sparrow, 2014). 300 -350 mm thick wall (not less than 250mm) is ideal to balance between high level of insulation and an excessively long drying time (Stanwix & Sparrow, 2014). Thermal: conductivity, capacity, effusivity and diffusivity , swelling and shrinkage and dampening of hempcrete and wood (radial) are almost identical, thus hemcrete does not behave as a thermal bridge and gives hempcrete a significant advantage (Alembic Studio, 2013; Bevan & Woolley, 2008, Evard, 2008; Evrard and De Herde, 2005). Once fully hardened, hempcrete provides 10 times more racking strength (rigidity) than the timber diagonal bracing to the frame structure due to its good tensile strength; adding ability to resist lateral (wind) load (Stanwix & Sparrow, 2014).

2.6 Industry Standards

Virtually, there are currently no industry standards for hempcrete; however, to some extent, some manufactureres/suppliers have established basic details/standards for their own use and hence, there is lack of clear cross-industry standards (Stanwix & Sparrow, 2014). As a rule of thumb, all the structural elements (timber, metal etc.) should have hempcrete covering to its width (Figure 3) but not less than 70mm (during BRE test for severe driving rain for 96 hours on a 200mm hempcrete wall, maximum water ingress was recorded up to 70mm) (Stanwix & Sparrow, 2014). The authors, in this regard, suggest that if driving rain is a regular feature on the site, clad walls with a breathable membrane and ventilated air gap will be better option to just lime rendered hempcrete wall . In addition, to restrict ingress in wall from driving rain, sufficient overhang from roof and windows/doors will be beneficial. A drip detail incorporated into the bottom of the render of wall also stops water from running down the plinth. Moreover, to keep the wall free from rain splashback hitting the ground , plinth should be maintained at least 150mm high (Stanwix & Sparrow, 2014). However, Evard & De Herde (2005) argues that hempcrete wall must be protected inside and outside.

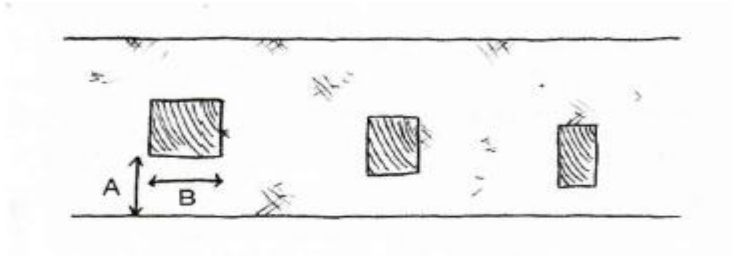


Figure 3: The coverage of hempcrete over timber/metal

(Stanwix & Sparrow, 2014)

Nowadays, behavior of building components under natural climate is analyzed through dynamic modelling (such as WUFI) and transient behaviors of components on thermal, air flow or moisture (HAM) gives realistic results that help designers to optimize the performances of the buildings (Evard, 2008). “In 2002, an important synthesis of laboratory experiments made on hempcrete was generated. It gathered what was considered as the state of the art” (Evard, 2008); where, specific multiple porosity as well as high hygroscopic and capillary transfers of hempcrete were pointed out.

2.7 Methods of Production

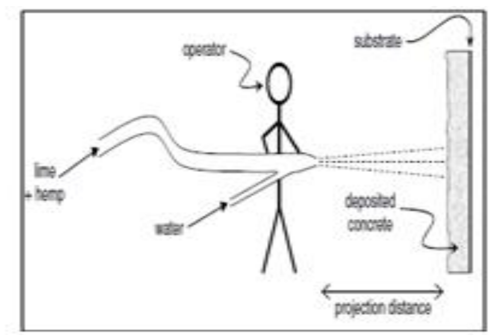
Hempcrete implies low-tech nature of construction method and can be produced by 3 processes: spraying (shot concrete or shotcrete), moulding (monolithic) and precasting (Figures 4-5) (Collet & Pretot, 2014). Cast-in-situ (moulding) by hand-placing is usually preferred one because of low embodied carbon and monolithic insulation layer which creates an air-tight system (Stanwix & Sparrow, 2014; Bevan and Woolley, 2008). Furthermore, hempcrete is recommended to cast above 5^0C, in the layers of 100-150mm, up to 600mm height in one go (lift) (Stanwix & Sparrow, 2014).

Most common mixing options for hempcrete are either using mechanical mixers such as forced-action pan mixture or bell (drum) mixer (Stanwix & Sparrow, 2014).However, regular mortar mixer was used by Woolley in his workshop at Endeavour Centre, ON to mix cast-in-situ hempcrete (Magwood, 2013).

Figure 4: Hempcrete building-under construction

(Maher, 2014)

Cast in Situ (Maher, 2014)



Projection (Spraying) (Elfordy et al, 2008)

Figure 5: Production methods

2.8 Drying

The “resting moisture content” (a natural equilibrium level) in hempcrete wall after drying can be expected around 15% and the ideal timing to apply finishing would be when WME is less than 23% in surface and 35-40% in below the surface (Stanwix & Sparrow, 2014). Stanwix & Sparrow (2014) presumed drying time of 6-8 weeks for 300mm wall, but surprisingly drying time anticipated by Magwood (2013) in their test for 350mm thick wall at Endevour Centre, ON was just 2 weeks. However, Colinart et al (2008) found the stabilization of mass and the drying of hempcrete block proceeds in about 70 days. Moreover, drying times also depend up to the type of binder used (hydraulic lime binder demands less drying time than hydrated one) and positioning (tamp or loose). However, leaving one face of the walls without finishing for longest possible time optimizes moisture release (Stanwix & Sparrow, 2014). It is also to be considered for air gap when hempcrete connects with other materials, because it fairly shrinks when it dries out. In addition, being hempcrete highly alkaline (pH >7) anything incased in it should be highly corrosion resistant; leading the safest option of timber (Stanwix & Sparrow, 2014).

2.9 Production of Hemp/Hempcrete building in Canada

As mentioned earlier, Canada has ample production of hemp (Endeavour Centre, ON and National Industrial Hemp Strategy, 2008). In 2013 there were 66,671 acres licensed for cultivation and hemp has been grown with success from coast–to–coast (Canadian Hemp Trade Alliance, 2015). Lime binder is sourced from North America and available in local stores; hence, the whole production cycle for hempcrete comes from a reasonable radius of central Canada (Magwood, 2013). The Arts Centre Hasting, the Camp Kawartha Environment Centre and The Camp Maple Leaf Family Cabin, Ontario are some of the examples of local produced hempcrete construction by Endeavour Centre, ON.

2.10 Life Cycle Analysis (LCA) and Embodied Carbon

BCB-Lhoist & Construire en chanvre (2005) conducted lifecycle analysis (cradle to grave) for 1 m2 wall of banked hempcrete on a wooden skeleton in the context of Europe (Spain) regarding the “green house effect over 100 years” (considering 3 carbon absorbers- hemp shiv, lime and wood) and found that hempcrete wall with wooden studs stores more carbon by photosynthesis and recarbonation (68 kg CO2e) than emitted by lifecycle (33 kg CO2e); representing net balance of 35 kg CO2e (14 kg CO2e for economic allocation) over 100 years per m2 (Arnaud & Amziane, 2013). Similarly, in the other study of Miskin (2010) embodied carbon of hempcrete (per m2) at 100mm thickness (taking account of installation, maintenance and end of life disposal) found was -0.08 $kgCO_2m^2$ (Wright et al, 2012). Meanwhile, maximum carbon emitted during hempcrete production claimed by Woolley (2012) was 8 MJ/kg (Hemp-2.5MJ/kg -2.8 MJ/kg, Binders- 4.5MJ/kg -5.3MJ/kg). (For figure and tables on LCA, see Appendix A).

2.11 Mechanical Properties

Hemprcrete, with flexible hemp and rigid binder leads to a non-fragile elasto-plastic behavior and is differentiate from other construction materials by a high deformability under stress, lack of fracturing and high ductility with absorbance of the strains ever after having reached the maximum mechanical strength (Arnaud & Amziane, 2013). Meanwhile, Cerezo (2005) states that mechanical properties of hempcrete are too low (0.05 to 0.35 MPa) to consider it as a structural material (Cerezo, as cited in Lawrence et al, 2012). Walker & Pavia (2014) concluded that increasing binder hydraulicity enhances early strength development but does not significantly affect ultimate strength – all hempcretes reach similar strength at 1 year irrespective of the binder type (0.29– 0.39 MPa). It was also concluded that the hempcrete is sensitive to freeze–thaw (10 cycles); however, salt exposure (1 month) and biodeterioration (7 month exposure) did not have a detrimental impact on the hempcrete (Walker & Pavia, 2014). In the study of Pinkos et al (2011), the low values for Young's Modulus showed that hempcrete can withstand significant geometric changes under residual stress. However, there should always be a good compromise between the thermal and mechanical properties in the wall construction (Colinart et al, 2012). Moreover, in the study of Lanos and Collet (2011) compression strength of hempcrete found was 0.2- 3.5 MPa.

2.12 Benefits of Hempcrete

2.12.1 Environmental Benefit

2.12.1.1 Carbon Sequestration and Saving

According to Eberlin & Jankovic (2015), Carbon Sequestration of Hempcrete is -133kgCO_2/m^3. However, Bevan and Wooley (2008) claim it is -108kgCO_2/m3.

2.12.2 Other Benefits

2.12.2.1 Insulation, Thermal Mass and Comfort

Hempcrete wall provides high level of insulation (because of trapped air in pore space) and has greater heat storage (thermal) capacity than concrete block, mineral wool and clay brick (Stanwix & Sparrow, 2014; Bevan & Woolley, 2008). Hempcrete; both insulates and stores heat and balances thermal and humidity variations as required (retaining of heat and cooling as well). It absorbs and releases energy, as moisture is released or absorbed (Bevan and Woolley, 2008). Hempcrete normally stays in the hygroscopic (hygroscopic adsorption) region i.e. about 90%RH; however, others are normally in the range of 40 to 70% RH. This small amount of moisture in the hemcrete plays an important role in its thermal performance by adding a phase change property. This is where the moisture changes from liquid to vapor, or back, stores or releases energy (Evrard and De Herde, 2005). It slows down the quick flow of heat when temperature changes abruptly (thermal shock) and hence can maintain much more thermally stable conditions (Bevan & Woolley, 2008). For 250mm hempcrete wall, in sudden cooling (thermal shock) of 0°C from 20^{0}C took 72 hours to reach a steady state of heat transfer and the heat loss in the first 24 hours was 187 KJ/m2 (0.11 W/m2 K), very less comparing to other insulating materials. Moreover, low thermal diffusivity and effusivity of hempcrete denotes that it will take longer time to change temperature (time lag or decrement delay) in heat transmission and feels warm to the touch. This warm feeling very much improves the thermal comfort of a building (sub-conscious feelings of thermal comfort- that is average between air temperature and wall temperature, are achieved at an air temperature of 1 to 2 degrees lower than in conventional masonry structures). In this scenario, one feels warm even though the heating is turned down; saving in heating costs (Bevan & Woolley, 2008; Evrard & De Herde, 2005). Yates (2002) in BRE (GB) report stated that in the thermographic inspection of the masonry and hemp house; outside surface temperature of the hemp house was lower (approximately 4°C to 6°C) than the masonry wall and concluded that external walls of the hemp house retain more heat than those of the traditionally built masonry house (Evard, 2008).

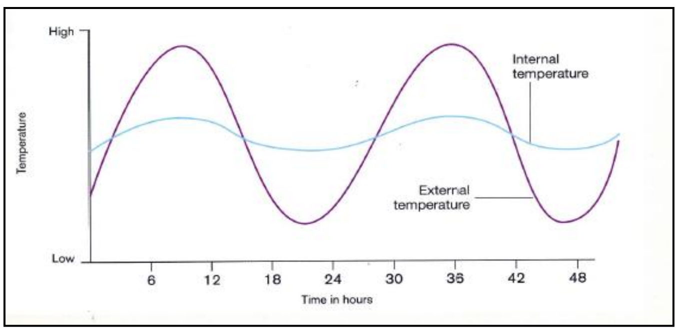


Figure 6: Hempcrete wall - maintaining a steady internal temperature

(Stanwix & Sparrow, 2014)

Figure 6 above confirms that the hempcrete walls create a very stable internal environment in the diurnal temperature variation too.

Material	% Dampening at 25 cm	Time Shift at 25 cm
Hempcrete	98.50%	15
Wood	98.80%	16
Cellular Concrete	95.00%	10.5
Mineral Wool	77.50%	6
CEM Concrete	89.50%	7

Table 1: Dampening of diurnal temperature variation at 250mm depth in hempcrete

(Evrard and De Herde, 2005)

Table 1 above shows 250mm of hemcrete wall could almost completely (98.5%) dampen a sinusoidal change in external temperature from 20^0C to 0^0C over a 24hr cycle and has the longer time shift of 15; better than 250mm high insulating material (mineral wool) (Evrard & De Herde, as cited in Alembic Studio, LLC, 2013).

2.12.2.2 Ventilation (Indoor Air Quality)

The breathable charachteristic of hempcrete allows moisture-laden air to permeate out through the envelope and this helps to maintain good indoor air quality. Likewise, moisture buffering capabilities (passive regulation of humidity) of hempcrete controls indoor humidity and reduces the problems of dampness and condensation and lessens the risk of mould growth (Bevan and Woolley, 2008). Moreover, there is no risk of “off-gassing” or toxicity during the use of building, or even at end-of-life demolition. In addition, relatively high thermal mass of it also maintains indoor air quality (Stanwix & Sparrow, 2014).

2.12.2.3 Air Tightness

Hempcrete, a monolithic material, is inherently airtight (Stanwix & Sparrow, 2014). Tests carried out on Commercial Tradical Hemcrete buildings (UK) have achieved air leakage value of around $2m^3/h\ m^2$ at 50 Pa (Bevan and Woolley, 2008). Similarly, Serve Project at Cloughjordan Ecovillage, Ireland also showed an airtightness level of 1.2 m^3/hm^2at 50 Pa (Stanwix & Sparrow, 2014). From this it can be depicted that hempcrete has a good airtightness property. In this regard, Brennan et al (2007) claims that for air-conditioned office buildings, best practice is 2 m^3/hm^2 at 50 Pa, and normal is 5 m^3/hm^2.

2.12.2.4 Fire Safety

Hempcrete solid mass if used with timber frame (composite), it is almost impossible to catch fire (Bevan and Woolley, 2008). When fire tests were carried out on 250 mm thick walls of hemp lime blocks laid in a lime mortar, no emissions of toxic material and no re-ignition were found. During fire test, the wall remained undamaged for 1 hour 40 minutes without failure (Bevan and Woolley, 2008). Similarly, for cast-in-situ, in BRE group’s fire test to internal face of the wall, it resisted fire for 73 minutes (Stanwix & Sparrow, 2014).In this regard, OBC (1997),Clause

9.10.14.12(2)(a) requires minimum 45 minutes of fire rating for exposing building face of a house with a limiting distance less than 1.2m .

2.13 Comparing hempcrete to other sustainable building materials

Properties	Hempcrete	Straw Bale	Brick	Mud Brick
Thermal Conductivity "k" (W/mK)	0.065	0.052	0.137	0.51
Construction Cost	Lowest	Lowest	Lowest	More Expensive
Workability	Easy and Fast	Easy and Fast	Experience required	Difficult
Pest	Pest Proof	Risk	Pest Proof	Termites
Fire Resistance	Fireproof	Depends on Render	Externally Fireproof	Externally Fireproof
Density (kg/m3)	275	90-120	750-790	800
Embodied Energy	Low EE	Low EE	High EE	Low EE
Carbon Foot Print	Absorbs CO2	Absorbs during growing	High (kiln Fired)	Neutral
Damp and Rot	Rot Resistant	Can rot if wet	Damp Proof	Relies on roof overhang
Recycling	Fully Recycled	Used as mulch	Recycled/high cost	Fully Recycled

Table 2: Properties of hempcrete and other materials

(Bedliva & Isaacs, 2014)

While comparing hempcrete (Table 2) with other sustainable materials (straw bale, brick and mud brick), its performance on all the parameters (thermal conductivity, construction cost, workability, fire resistance, density, embodied energy, carbon footprint and recycling) was quite satisfactory.

3.0. Literature Review

3.1 Moisture retention and influence

3.1.1 Moisture Transfer

Major moisture transfer mechanisms in the hempcrete are rain, condensation, rising damp and initial moisture (Kunzel, as cited in Tolkovsky, 2010).

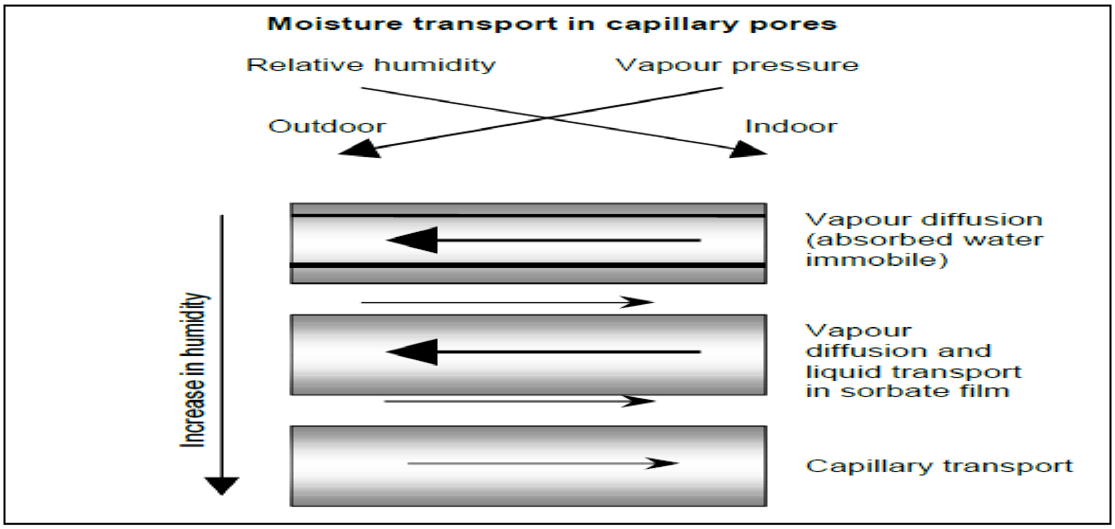


Figure 7: Moisture transport in a porous hygroscopic building material

(Tolkovsky, 2010)

As shown in Figure 7, the gradients of vapor pressure and relative humidity are running in inverse directions. The higher the moisture of the building component, the higher the liquid transport in terms of vapor diffusion until there is a reversal in transport direction. Hence, the potential for porous building elements to act as moisture buffering in the surrounding environment is as a response to rising relative humidity (Kunzel, as cited in Tolkovsky, 2010).

3.1.2 Moisture Retention Curve (Sorption Isotherm)

The sorption isotherm relates the amount of equilibrium moisture content to the ambient relative humidity for a given temperature (Collet et al, 2013). Evard (2008) states that like other materials with open-porous structure, hempcrete is also permeable to gas and liquid depending on their specific porous structure.

Moisture can be temporarily stored during transfer and as shown in Figure 8, 3 moisture storage regions - hygroscopic, capillary condensation and surface diffusion were detailed for hempcrete (porous materials) by Künzel (as cited in Evard, 2008).

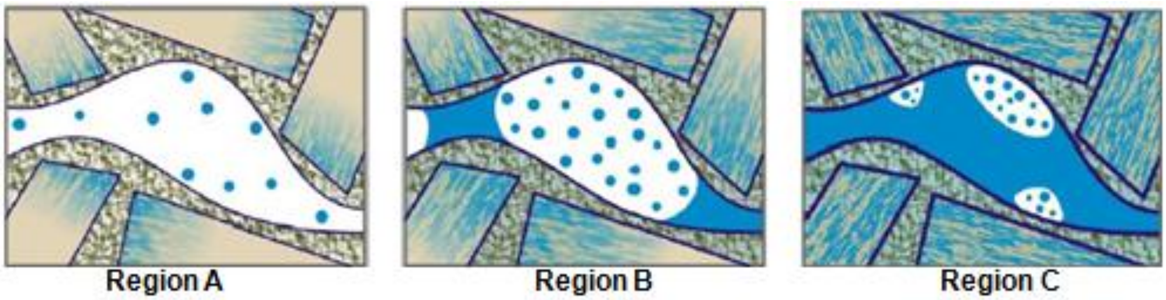


Figure 8: Moisture Storage Function

(Evard, 2008)

Region A (Sorption moisture, termed sorption isotherms in building physics or hygroscopic adsorption region): Rises from dry-state to high relative humidity (up to 93% RH in hempcrete), including all water contents resulting from water vapor sorption up to a state of equilibrium.

Region B (Capillary water or super-hygroscopic region): Follows sorption moisture region (from around 93% RH until free water or capillary saturation-100% RH). This region too is characterized by state of equilibrium. It starts when two phenomena- capillary condensations (condensation in the small pores) and surface diffusion (adsorbed film of water is thick enough to allow water movement) in porous structure of material start to be significant.

Region C (Supersaturated region): Follows free water (capillary) saturation by filling all cavities. It has no more state of equilibrium and RH is always 100% regardless of rise in water content. This region occurs through diffusion in temperature gradient (in practice) and suction under pressure (in laboratory) (Kunzel, as cited in Evard, 2008).

In summary:

1. Water bound through adsorption (Up to W_{93}): Hygroscopic Range (Sorption/Suction Isotherm)
2. Unbound Water (W_{93} to W_f): Capillary Condensation Range (Suction/Redistribution) (W_f : Maximum quantity of water that can be stored in material)

3. Super Saturation (W_f to W_{max}): Surface Diffusion (no state of equilibrium) (Kunzel, 1995).

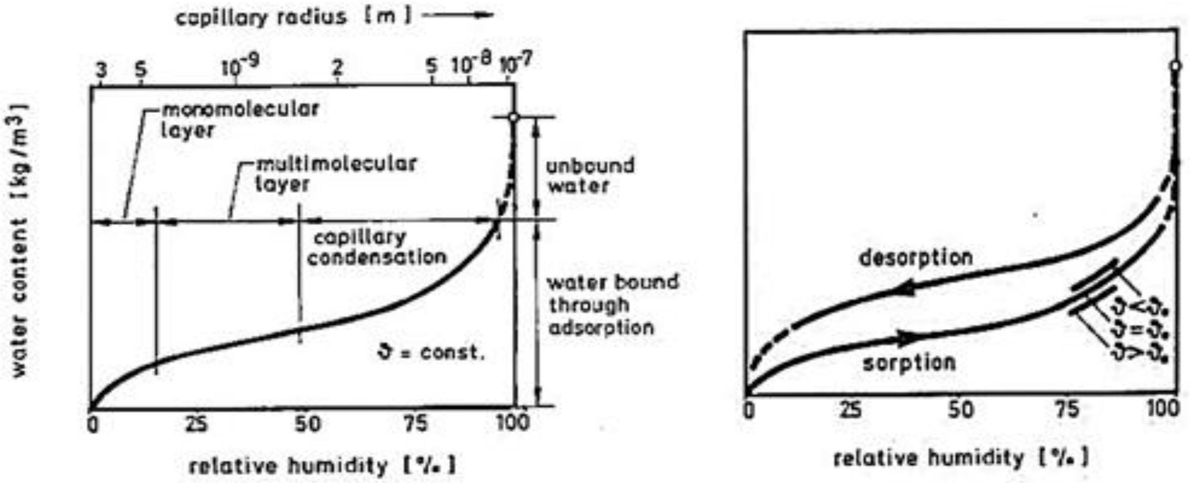


Figure 9: Sorption and Desorption

(Evard, 2008)

Figure 9 above shows that rising equilibrium (absorption) is slightly different form falling equilibrium (desorption). This hysteresis can be relatively important with specific pores geometry, especially in organic material (Krus, as cited in Evard, 2008).

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Relationship below presents the slope of MRC (Sorption Isotherm) curve, known to be (specific) hygric capacity ξ_ϕ . WC and ξ_ϕ are either expressed in %mass (%Mass = M_w/M_0) or kg/m3 by multiplying the results by ρ_0. $\xi_\phi(w) = dw/d\phi$ (Evard, 2008). In the hygroscopic region (up to 93% RH) sorption isotherm at 23°C is almost linear for hempcrete (Figure 10) and hygric capacity takes then a single value of10.2 % (Evard & De Herde , 2010).

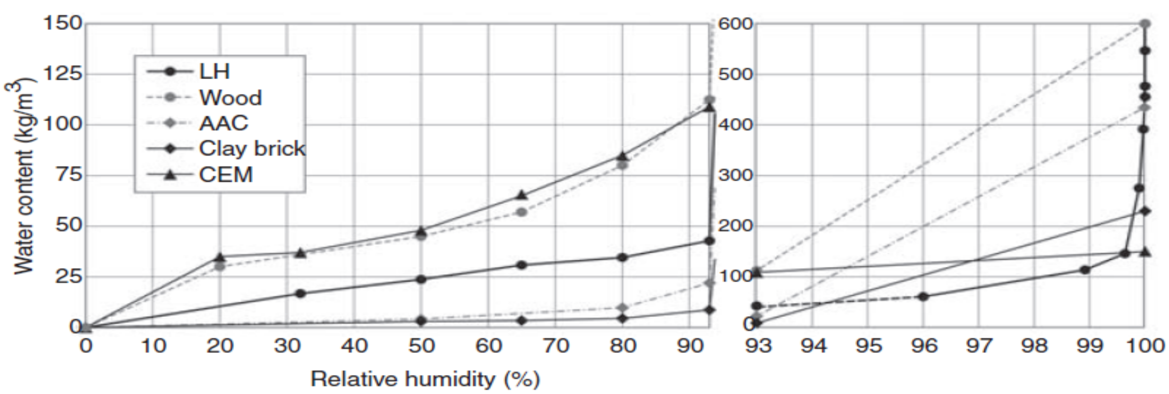


Figure 10: Moisture retention curve of hempcrete and other materials

(Evard and De Herde, 2010)

It is noticeable that (Figure 10) the value acquired for capillary region (above 93% RH) does not come from salt solution measurements for other materials, except for hempcrete.

The identical moisture sorption was obtained for hempcrete by Collet et al (2008) too (Evard & De Herde, 2010). In the another research of Evard (2008), following MRC (Figure 11) was obtained (300mm wall, 440kg/m3 density, hemp to binder ratio 1:2 and binder to water ratio 1:1.5).

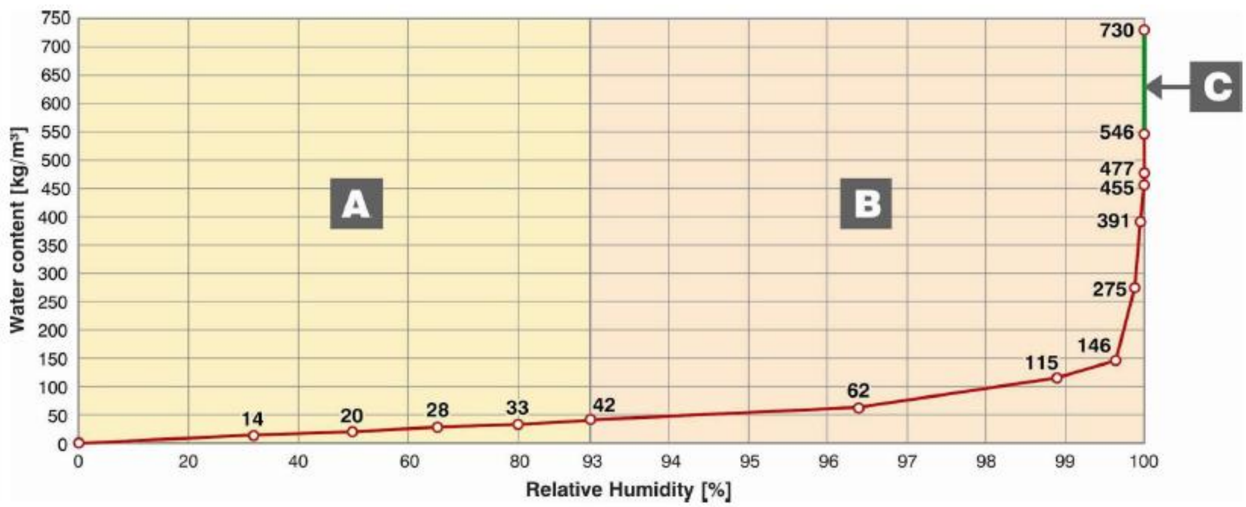


Figure 11: Complete MRC for hempcrete Wall

(Evard, 2008)

It appears that (Figure 11) hygroscopic region (region A) is up to 93% RH (almost linear sorption isotherm) and capillary region (region B) starts from around 93% of RH.

3.1.3 Moisture Buffer Value (MBV)

MBV represents the amount of water that is regulated in or out of a material per open space area during a certain period of time, when it is subjected to variations in RH of the surrounding environment (Rode et al, 2005). It is one of the best dynamical parameter (only sorption curve and water vapor permeability can't lead to a good prediction of hysteric behavior) to evaluate the moisture buffer capacity of materials; the higher it is, the stronger the component will regulate the internal ambient humidity (Evard & De Herde, 2010; Evard, 2008). In this regard, Collect el al (2013) adds that moisture buffer value is proportional to the moisture effusivity of the material (which is linked to the moisture permeability and to the derivative of the sorption isotherm) and is illustrated by the equation

MBV= Δm/A (RH_{high}-RH_{low})

Where, MBV= Moisture buffer value (kg/(m2 %RH), Δm= Moisture uptake/release during the period (kg), A= Open surface area (m2) and $RH_{high/low}$= High/low relative humidity level (%).

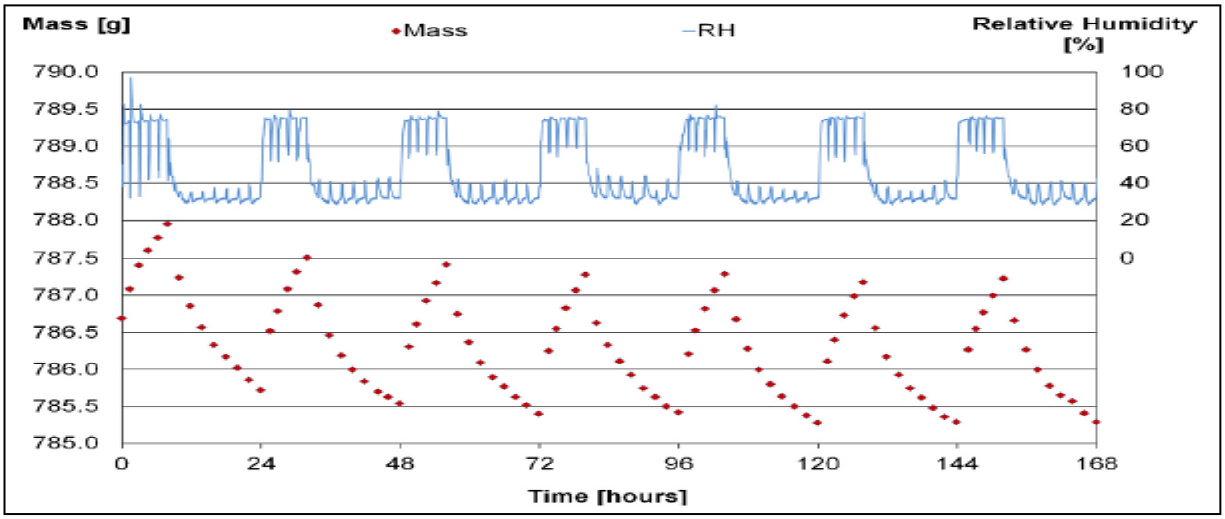


Figure 12: Moisture uptake and release and monitored RH

(Collet el al, 2013)

As shown in Figure 12 above, the steady state is reached from the fourth cycle; Δm and MBV varied less than 5% within each cycle. While calculating MBV from cycles 4 to 7 in adsorption and desorption, the average value found was 2.14 [g/(m^2 %RH)] (slightly higher in desorption than absorption) (density 430 kg/m3). Based on the classification of the NORDTEST Project, it can be concluded that hempcrete looks to be excellent hygric regulators (MBV >2 g/(m2 %RH), showing the ability to regulate ambient relative humidity (Collet et al, 2013). MBV for 300mm hempcrete wall found by Evard (2008) was also almost similar i.e. 2.11 [g/(m^2 %RH)].

3.2 Heat Flow through Surface

Heat flow through the surface is expressed by means of a heat transfer coefficient h_{surf} (W/m2K), and depends on convection and radiation h_{surf}= $h_{radiation}$+$h_{convection.}$ Heat transfer coefficient of inside surface (h_i) depends on the configuration of the wall assemblies plus the orientation of the heat flow. The heat transfer coefficient of an outside surface (h_e) is considered to be dependent to wind speed V_{wind} (m/s) (Evard, 2008). According to WUFI (Kunzel, 1995), heat flow resistance (outside) = [1.6 x V_{wind} + 4.5 (conv) + 6.5 (rad)] [W/m²K] or h_e = 1/Heat flow resistance [m2K/W].

3.3 Thermal Diffusivity and Effusivity

When hygrothermal conditions change at the surface of assemblies, hygrothermal distribution through the component are accommodated until permanent transfer corresponding to boundary conditions is reached. Thermal diffusivity α (m2/s) and effusivity Eff (J/m2 $Ks^{-1/2}$) can be defined to understand the material's behavior during transient transfer (Evard, 2008).

3.3.1Thermal Diffusivity (α)

Thermal diffusivity represents the rate at which the temperature of the material can vary; the lower it is the slower will change the temperature of the material. It is calculated as $\alpha = k / \rho c$; in dry state $\alpha_0 = k_0 / \rho_0 c_0$ (Evard, 2008).

Evard & De Herde (2005) and Evard (2008) in their studies of 250mm and 300mm thick hempcrete walls (hemp to binder: 1:2), α_0 found were 1.48 $\times 10^{-7}$ and 1.68 $\times 10^{-7}$ m2/s respectively; which were low compared to other insulation materials and were almost constant in all RH states.

3.3.2 Thermal Effusivity (Eff)

Thermal Effusivity constitutes the quantity of energy given to or out from a material when it is subjected to heating or cooling during a given time laps. It is responsible of warm (small Eff) or cold (big Eff) feeling when touching the material, hence, lower is better in cold climate. It is calculated as $Eff = (\rho c k)^{1/2}$; in dry state $Eff_0 = (\rho_0 c_0\ k_0)^{1/2}$(Evard, 2008).

Evard & De Herde (2005) and Evard (2008) in their studies of 250mm and 300mm thick hempcrete walls (hemp to binder: 1:2), Eff_0 found were 286 J/m2$Ks^{-1/2}$ and 297J/m2$Ks^{-1/2}$ respectively; which were low compared to other insulation materials and were almost constant until hygroscopic region (93% RH) but when approaching to free water saturation (100% RH), was ascended.

3.4 Hempcrete Buildings Performance

3.4.1 Hempcrete building compared with Cellular Concrete building

In the study of Tran Le et al (2010); hempcrete (density 413 kg/m3, k=0.1W/mK) and celluar concrete (density 600 kg/m3, k=0.14W/mK) buildings' performance were compared in the identical situation (room size 15m2 , volume 42.75m3; ceiling, west and south facades in contact with outdoor conditions; external walls and ceiling 300mm thick; no moisture diffusion through the floor ; room indoor temperature around 20^0C; ventilated at 0.5 ACH; heat transfer coefficients h_e =25W/m2 K and h_i=8W/m2 K) and found the followings.

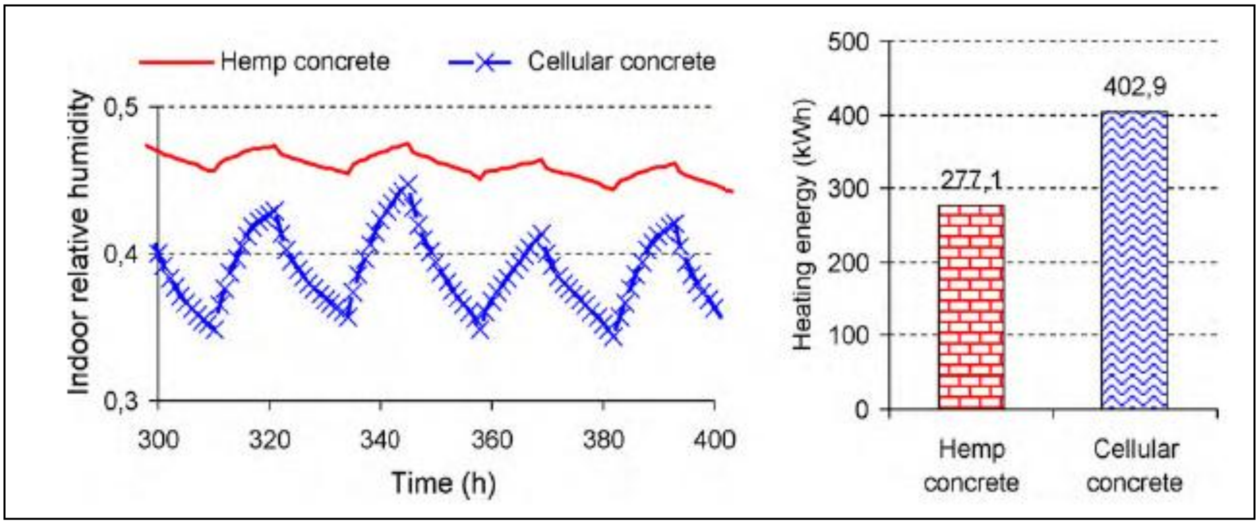


Figure 13: Variation of indoor relative humidity and heating energy

(Tran Le et al, 2010)

As shown in Figure 13, RH for the hemp concrete building was more (42% in hempcrete case and 35% in cellular concrete case) because of high hygroscopic capacity of hempcrete. At the same RH, MC of hempcrete was higher than that of cellular concrete and thus could regulate better indoor RH. Concerning energy consumption, hempcrete had lead to a reduction of 45% (125.8 KWh) than cellular concrete because of lower thermal conductivity (Tran Le et al, 2010).

3.4.2 Hempcrete building at Alternative Village, Manitoba University

To understand load and moisture behavior using Manitoba hemp for the use of hempcrete wall in a Northern Prairie Climate (in the test building located in the Alternative Village at the University of Manitoba), a study was conducted by Pinkos et al (2011). The building had conceded area of 23.8m2 and the walls were 300mm thick. The exterior was covered with a building wrap (Typar), rain-screen gap and wood sheathing. The interior was left unfinished to investigate the effect of an air barrier on the ability of hempcrete to manage moisture. Temperature, RH and energy consumption was monitored continuously. MC of the hempcrete (Figure 14) at 98% RH was found about 12% (MC below 20% dry basis is considered to be a reasonable threshold for hemp decay) (Pinkos et al, 2011). Temperature profiles through the wall indicated the hempcrete provided a stable temperature throughout the wall. Similarly, RH through the wall showed that the internal portion of the wall managed moisture in a consistent manner. Moreover, the power consumption of the hempcrete structure was 153.9 kWh. Although it may not have performed similar to the R2000 building (118.8kWh), an increase in wall thickness was likely to improve thermal performance (Dick, as cited in Crawford, 2013).

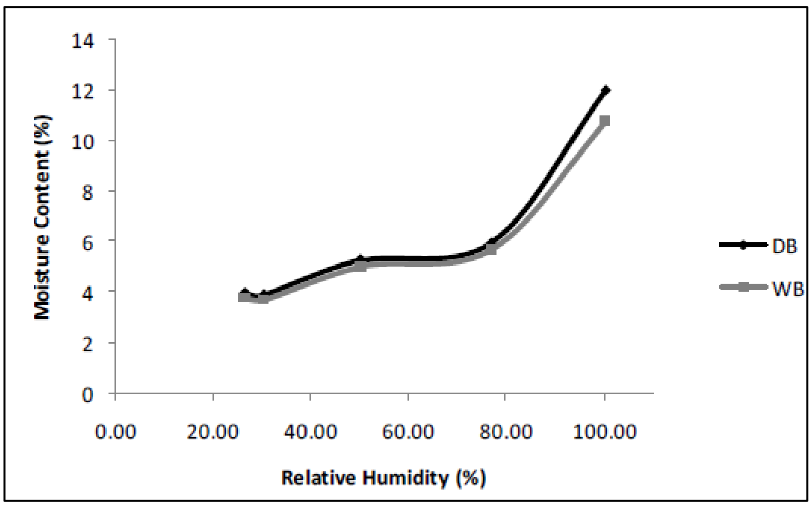


Figure 14: Sorption Curve, wet and dry basis

Source: Pinkos et al (2011)

3.4.3 Lime Technology office building, UK

The new Lime Technology office had 500mm thick hemcrete walls and had been monitored to check thermal performance. Figure below (Figure 15) shows the external temperature and RH (dotted lines) compared to internal temperatures and RH (solid lines). In the diurnal fluctuation of outside RH and temperature too, hempcrete wall maintained steady internal RH and temperature (Bevan & Woolley, 2008). However, it is to be noted that internal RH (about 68%) and temperature (about 15^{0}C) maintained by wall are still not sufficient to classical inside environment (20^{0}C, 50%).

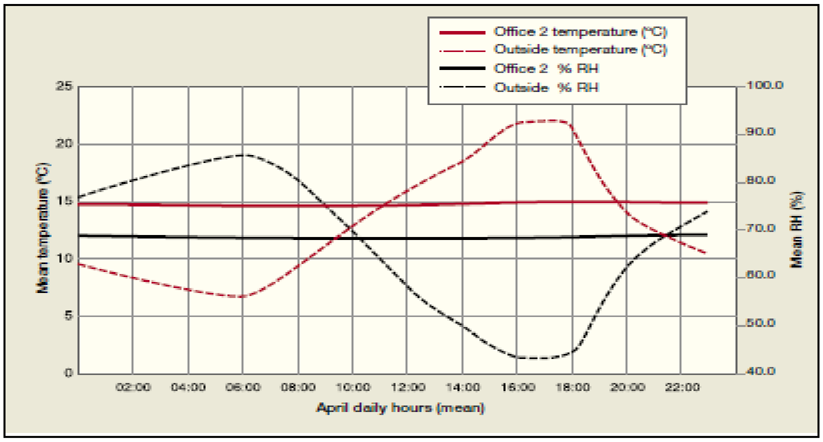


Figure 15: Monitoring of the Lime Technology Ltd head office (UK) during April 2007 (Bevan & Woolley, 2008)

3.5 "R" value

R-value is the resistance to heat flow of a homogenous layer or assembly of materials. According to Fourier's law, R = (ΔT A)/ Q = ΔT/q (lumps all three modes -conduction, convection and radiation into one metric).Subject to all heat flow by conduction, and all materials homogenous and no temperature sensitivities: R = d/k or 1/U.

Where,

Q = Rate of heat flow (W), k = Thermal conductivity (W/mK), d = Thickness (m)

ΔT = Temperature difference (K), A = Area through which heat flow is measured (m^2)

R = Thermal resistance (m^2K/W), q= Heat flux (W/m2), U= Thermal Conductance (k/L) (W/m^2K)

ASTM C 518, ASTM C177, ASTM C1363, ASTM C 1046, ASTM C1113/C1113M and ASTM C1114 are some of the most common thermal property testing methods (standards) listed in the FTC (Federal Trade Commission) rule. Clear wall R-value (containing only insulation and structural framing materials, excluding fenestration etc.) is used to define the thermal performance of enclosures in ASHRAE Standard 90.1. However, Center of Cavity (Nominal) - at mid-height and Whole wall -for the whole opaque wall are other forms of R value (Straube, 2007). It is considered that actual R-values of walls are lower than the clear wall analysis due to thermal bridging from studs (Straube, 2007).

Regarding R values of hempcrete wall, a 300 mm to 350 mm thick wall can produce an insulating value of R-20 to R-30 (R 2.5/inch) depending on the mix (Oliver, as cited in Kenter, 2015). However, Magwood (2013), Stanwix & Sparrow (2014) and Alembic Studio, LLC (2013) expect R2.0- R2.5/inch in hempcrete. But, Maher (2014) claims hempcrete gives R value between 2.5 to 3.0/inch.

Density (kg/m3)	Wall Thickness (mm)	U-value (W/m2K)	R-value (m2K/W)
220 kg/m3	300 mm 350 mm	0.167 0.143	6.00 (R34) 7.00 (R40)
275 kg/m3	300 mm 350 mm	0.20 0.171	5.00 (R28) 5.85 (R33)
330 kg/m3	300 mm 350 mm	0.23 0.197	4.35 (R25) 5.08 (R29)

Table 3: Hempcrete "U" and "R" values for different densities and thicknesses

(Ahlberg et al, 2014)

As shown in Tables 3-4, k and U values are directly proportional to density (k or U ∝ Density), when density increases, k or U increases; in contrast R is inversely proportional to density (R ∝1/ Density), when density increases R value decreases.

Wall Thickness (mm)	300	400	500
U-value (W/m2K)	0.23	0.18	0.14
R-value (m2K/W)	4.35 (25)	5.56 (R 33)	7.14 (R 50)

(Alembic Studio, LLC, 2013)

Wall Thickness (mm)	250	300	350	400
U-value (W/m2K)	0.23	0.20	0.17	0.15
R-value (m2K/W)	4.35 (R 25)	5.00 (R 28)	5.88 (R 33)	6.67 (R 38)

(Stanwix & Sparrow, 2014)

Table 4: R-values for different thickness of walls

Even better R –values than theoretical one was witnessed in the dynamic condition of the real building in in-situ tests (Stanwix & Sparrow, 2014).

In addition to R-value, thermal bridging, phase change, thermal mass, air leakage (infiltration/exfiltration), wind washing, air-pumping, change of property of material over time (aging), convective loops etc. factors also influence the thermal performance of the components. Hence, to achieve high thermal operation by enclosures, along with R-value due consideration should be given to all those specified factors too (Straube, 2007).

3.6 Hygrothermal Parameters

3.6.1 Hygrothermal Parameters in Dry State

3.6.1.1 Dry Density (ρ_0)

Dry density is considered as density of the materials at fully dried state. Evard (2008), in his experiment, introduced the samples in an oven at 40°C with dry air supply, mass equilibrium was considered to be reached when mass measurement varied less than 1% between 2 measurements on a 24h basis and measured dry density by following the equation $\rho_0 = \rho\text{-}w$. Reference dry densities obtained during literature review are highlighted in Table 5.

S. No.	Reference	Mix Proportions (Hemp to Binder)	Dry Density (kg/m3)	Application
1	Cerezo (as cited in Lawrence et al, 2012)	(1:1)	220	Roof
		(1:1.5)	275	Wall
		(1:2)	330	Wall
		(1:2) Compressed	440	Wall
		(1:3)	500	Floor
		(1:4)	600	Floor
2	Evard (2008)	(1:2) Compressed	440±20	Wall
3	Evard (2006)	(1:2) Compressed	361- 466	Wall
4	Evard & Herde (2005)	(1:2) Compressed	480	Wall
5	Tran Le (2010)	(1:2) Compressed	413	Wall
6	Collet et al (2013)	(1:2) Compressed	430	Wall
7	Collet & Pretot (2014)	(1:2)	381	Wall
8	Walker & Pavia (2014)	(1:2) Compressed	531-627	Wall
9	Abbott (2014)	Not mentioned	275	Wall
10	Mawditt (2008)	Not mentioned	330 ±10	Wall
11	Woolley (2008)	Not mentioned	300- 400	Wall

Table 5: Reference Dry Densities

3.6.1.2 Porosity (Φ)

Porosity (Φ) or Void Volume (m^3/m^3) = $[(W_{b(5hr)\ or\ Sat} - W_O)/\ \rho_{Water}]/\ V_{ol}$ (ASTM C67) or Void Space/V_{ol} (Mensinga, 2009) or $W_{Max}/\ \rho_{Water}$ (Evard, 2008).

Hempcrete has both micro scale (within hemp hurd) and macro scale (within hempcrete) porosities. At a macro scale, the porosity due to the arrangement between the hemp shiv and the binder adhesion can reach a millimetric width (Figure 16) (Collet et al. 2013). The pores are interconnected, large pores open on smaller ones (pores in hemp particles ~10μm) through the porosity of the lime binder (~1μm) (Evard, 2008).

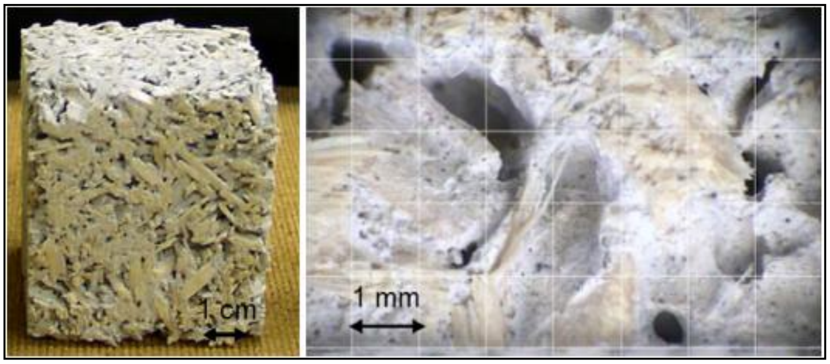


Figure 16: Porosity of hemp concrete at macroscale

Source: Collet et al (2013)

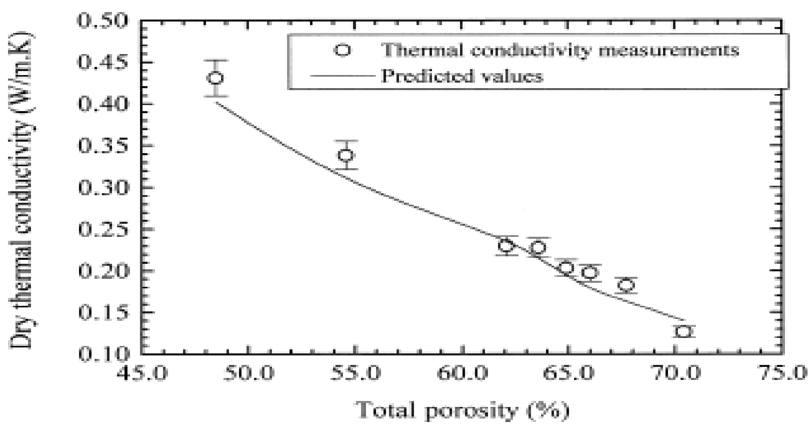


Figure 17: Porosity vs Dry thermal conductivity

(Bouguerra et al, 1998)

Figure 17 manifests that thermal conductivity and porosity has inverse relation (Conductivity ∝ 1/Porosity); when porosity increases, thermal conductivity value decreases, vice versa. The slope of porosity vs conductivity is quasi linear (Bouguerra et al, 1998).

Porosity was measured through dynamic test by Evard, 2008 by crushing the samples- solid mass was measured in the helium pyknometer and Φ was defined as $\Phi_0 = 100 \times (1- \rho_0/ \rho_{solid})$. The measured porosity was 73% by volume (for density 440kg/m3). Bouguerra et al (1998) measured porosity through mercury intrusion and vacuum saturation. In other studies, total porosity found was 79.0% (density 430 kg/m3) by Collet et al (2013), 71.1% (density 480 kg/m3) by Evard & Herde (2005), 84.3% (density 381 kg/m3) by Collet & Pretot (2014) and 71.1% (density 330kg/m3) by Mawditt (2008).

3.6.1.3 Dry Thermal (Specific Heat) Capacity (c_0)

Thermal capacity of materials denotes its ability to store heat. It is determined through $c_0 = c_w.m_w.(\theta_{end} - \theta_{init,w}) / m_0.(\theta_{end} - \theta_{init})$. To measure dry thermal capacity, Evard (2008) heated the samples to θ_{init} = 100°C (ISO 11357-4), then introduced into an adiabatic can filled with water at $\theta_{init,w}$ = 22°C (room temperature). Water temperature was measured until new equilibrium (θ_{end} [°C]). The method was also validated with measurement on aluminum samples (c_{alu} = 920 J/kg K). Mean dry thermal capacity of wall (density 440kg/m3) found was c_0 = 1560 ± 30 J/kg.

Walker & Pavia (2014) used insulated containers filled with water at 15^0C, dry samples (heated to 100^0C in an oven for 24 hours) were placed in it and the temperature rise of the water monitored at 15 min intervals. The water temperature achieved equilibrium after 2 h. The temperature increase of the water was used to calculate the heat capacity of the hempcrete. The average specific heat capacity of the hempcrete ranged from 1240 to 1350J/kg K for density 531-627 kg/m3 (for commercial mix- 1300 J/kg K, density 627kg/m3).

In other studies results found were 1000 J/kg K for density 430 kg/m3 by Collet et al (2013), 1550 J/kg K for density 480 kg/m^3 by Evard & De Herde (2005), 1550 J/kgK for density 330 ±10 kg/m^3 by Mawditt (2008), 1000 J/kg K for density 413 kg/m3 by Tran Le et al (2010), and 1500-1700 J/kg K for density 275kg/m^3 by Abbott (2014).

3.6.1.4 Dry Thermal Conductivity (k_0)

Thermal conductivity (“k”- W/mK) is a material property that indicates the quantity of heat flow across a unit area, through a unit thickness for a temperature gradient of 1^0C (Straube, 2007). It is the ratio between the density of heat flow rate and the extent of the thermal gradient at that point in the direction of flow (Tolkovsky, 2010). “k” depends primarily on the density of the material and increases in a quasi linear manner in relation to it (Elfordy et al, 2008). The study for thermal conductivity versus water content and density by Collet & Pretot (2014) shows that water content has a lower effect than density on thermal conductivity (“k” increase lower than 15 to 20% for a wide range of RH); however, thermal conductivity for high density is higher than twice the value for low density with the same formulation. Moreover, Cerezo (2005) had established a relation of density vs "k" through the equation (k = 0.0002 x ρ + 0.0194) (Walker & Pavia (2014).

Dry thermal conductivity k_0 (W/mK) (the rate of the passage of heat flow through the material) was measured following ASTM C518 by Evard (2008). According to experiment, each sample was dried, subjected to a temperature difference of ΔT=10°C between a hot and a cold plate at three different temperature steps. The mean temperature was respectively 18 ± 0.2°C, 26 ± 0.2°C and 34 ± 0.3°C. Reference value (k_0) for wall mixture (density 440kg/m3) measured was 0.115 ± 0.006 (W/mK) (the mean value of extrapolation of results at 10°C).

Arnaud & Amziane (2013) conducted test by drying the samples in oven (50^0C for 24 hours) in a permanent regime with guarded hot boxes (ASTM C1113) between 5^0C and 20^0C and found "k" as 0.064 W/mK (density 220 kg/m3) to 0.09 W/mK (density 450kg/m3). Collet & Pretot (2014) measured thermal conductivity (W/mK) using the commercial CT-meter device (ASTM C1113) and measured "k" as 0.13W/mK (density 377 kg/m3). Walker & Pavia (2014) tested conductivity according to ASTM C1155 with average temperatures 27^0C (interior) and 16^0C (exterior) and recorded k- value in the range of 0.117 to 0.138W/mK (density 531-627 kg/m3). Awwad et al (2013) conducted conductivity test as per ASTM C518 for concrete masonry blocks reinforced with hemp fibers and hurds and found "k" 0.984 W/mK. Moreover, Picandet et al (2012) tested the sample maintaining T_h 25^0C and T_c 15^0C (ΔT=10°C).

In other studies "k" were found as 0.06 - 0.12 W/mK (density 250-660 kg/m3) (Arnaud & Gourlay, 2012), 0.05 -0.12 W/mK (density 300-400 kg/m3)(Woolley, 2012), 0.076 - 0.11 W/mK (Rhydwen, 2006), 0.06-0.12 W/mK (Stanwix & Sparrow, 2014), 0.06 W/mK (density 275 kg/m3) (Abbott, 2014), 0.0697 ±5% W/mK (density 330 ±10 kg/m^3) (Mawditt, 2008), 0.11W/mK (density 480 kg/m3) (Evard & Herde, 2005), 0.065 W/mK (density 275kg/m3) (Bedliva & Isaacs, 2014), 0.179- 0.485 (density 417- 551 kg/m3) (Elfordy et al , 2008), 0.10 W/mK (density 413 kg/m3) (Tran Le et al, 2010), 0.06 W/mK (density 220kg/m3) to 0.115 W/mK (density 440 kg/m3) (Cerezo, as cited in Lawrence et al, 2012).

3.6.1.5 Dry vapor permeability/ Dry Vapor diffusion resistance factor (μ_0)

According to Walker & Pavia (2014), water vapor permeability is related with the water vapor diffusion resistance factor (μ); lower the μ, higher the permeability and expressed as

$$\mu = \frac{\text{Resistance to moisture movement of the material}}{\text{Resistance to moisture movement of the air}}$$

To find the dry vapor diffusion resistance factor μ_0, it is necessary to define the vapor diffusion thickness Sd [m] (the thickness of the equivalent air layer in terms of vapor permeability). Sd-value is calculated with Sd = μd. Similarly, dry vapor permeability is measured through $\delta_0 = (\delta_a / \mu_0)$ (Evard, 2008).

Evard (2008) measured water vapor permeability or dry vapor diffusion resistance factor μ_0 by following “Dry cup method” (EN ISO 12572). The samples were sealed on glass cups with paraffin (paraffin avoids any vapor transfer on the sides of the samples; the moisture flow can only go through top surface). Glass cups were filled with silica gel, leaving a 2 cm air layer under the sample surface (RH of 3% when the silica gel was dried before the experiment). The samples were then introduced in a climate chamber at 50% RH (23°C).The reference dry vapor diffusion resistance factor found was $\mu_0 = 4.85 \pm 0.24$ and dry vapor permeability as 1.56 ± 0.08).10^{-7} kg/msPa (for density 440kg/m3).

In another experiment by Walker & Pavia (2014), the specimens were placed on a dish with one side exposed to the humid environment of the curing room (20^0C, 50 % RH) and the underside exposed to the dish containing 75 g of calcium chloride, a desiccant that maintains RH at 0%. The transfer of water vapor was measured by weighing the test assembly (specimen and dish) over time. However, Collet et al (2013) used wet cup method to measure water vapor permeability (water vapor diffusion resistance factor).

Hempcrete has high moisture permeability; moulded hempcrete (density 430kg/m3) range water vapour permeability from 1.7×10^{-11} to 1.7×10^{-10} kg m^{-1} s^{-1} Pa^{-1}(Collet et al, 2013). Subsequently, Walker & Pavia (2014) for densities 531-627 kg/m3) found water vapor diffusion resistance factor (μ) ranging from 5.47 to 5.71, whereas permeability ranges from 3.99 $\times 10^{-10}$ to 4.21×10^{-10} kg m^{-1} s^{-1} Pa^{-1}. For a density of 330 ±10 kg/m³, μ recorded was 4.85 ± 0.24 (Mawditt, 2008). For density 361- 466kg/m3, μ was 3.59-7.68 (Evard, 2006) and for density 275kg/m3, μ was 4.84 (Abbot, 2014).

3.6.2 Hygrothermal Parameters in Moist State

3.6.2.1 Free Water Saturation (W_f)

Free water saturation (W_f) is the amount of water a material absorbs at 100% RH or the water content at free saturation. To measure Moisture Content (Sorption Isotherm), at 100% RH (W_f) for hempcrete, Collet et al (2013) used Climatic Chamber and Pinkos et al (2011) used desiccant with saturated solution of Potassium Dichromate ($K_2Cr_2O_7$) and Tolkovsky (2009) used Potassium Sulphate (K_2SO_4). However, for brick, Rose et al (2014) used submersion method for 24 hours in cold water.

Evard (2008) used pressure plate apparatus (ASTM C1699) to measure water content in higher humidity (between 93% and 100%) and found W_f as 124 ± 3,5 %mass = 546 ± 16 kg/m3 (density 440 kg/m3) (see Figure 11). Evard & De Herde (2005) in another study found W_f as 596kg/m3 (124%mass) (density 480kg /m3).

3.6.2.2 Maximum Water Content (W_{max})

Maximum Water Content (W_{max}) is the water content at fully saturation or the state where the porous structure is considered to be completely filled with water. Its value is given by W_{max}= Porosity (Φ) x ρ_{water} (at 23^{0}C, $\rho_{water} \approx$ 1000kg/m3) (Evard, 2008).

W_{max} defined through porosity were 730kg/m3 (166 ± 3 %mass, porosity 73%, density 440 ± 20 kg/m3) by Evard (2008), 790 kg/m3 (porosity 79.0% , density 430 kg/m3) by Collet et al (2013), 711 kg/m3 (porosity 71.1%, density 480 kg/m3) by Evard & De Herde (2005), 843 kg/m3 (porosity 84.3%,density 381 kg/m3) by Collet & Pretot (2014) and 711 kg/m3 (porosity 71.1%, density 330kg/m3) by Mawditt (2008).

3.6.2.3 Water Content at 80% RH ($MC_{RH\ 80\%\ Equivalent}$)

To measure $MC_{RH\ 80\%\ Equivalent}$, Evard (2008) and Collet et al (2013) used Climatic Chamber and Pinkos et al (2011) and Tolkovsky (2009) used desiccant with saturated solution of Sodium Chloride (Common Salt) (Nac l). $MC_{RH\ 80\%\ Equivalent}$ found by Evard (2008) was 33 kg/m3 (7.5%

mass, density 440 kg/m3) and Evard & De Herde (2005) was 36kg/m3 (7.5% mass, density 480kg /m3). Hence, for hempcrete, 7.5%mass will be the reasonable value for $MC_{RH\ 80\%\ Equivalent}$.

3.6.2.4 Thermal Conductivity Supplement (moisture-induced supplement) (b)

Thermal conductivity supplement, b [%/%mass] quantifies the increase of thermal conductivity [in (%) referring to dry value] when the water content rises of 1% referring to dry mass (Evard, 2008).

To determine “b”, a test was conducted by Evard (2008) to find “k” in moist state in RH 80% (WC= 33kg/m3) and RH 65%(WC=28kg/m3) for 2 samples. The mean temperature set for test was respectively 18 °C, 26°C and 34°C. Reference mean “k” value in moist state (0.127 ±0.002) and “b” value (3.34 ± 0.24 %/%mass) found were the mean value of extrapolation of results at 10°C (DIN 4108-4)(for the density 440 kg/m3). In this regard, Evard (2008) claims that based on the numeric relationship $k_w= [1+ (b\ w/\rho_0)]\ k_0$ or $b= \rho_0\ (k-k_0)/k_0\ w$, thermal conductivity in moist state for hempcrete can be hypothesized.

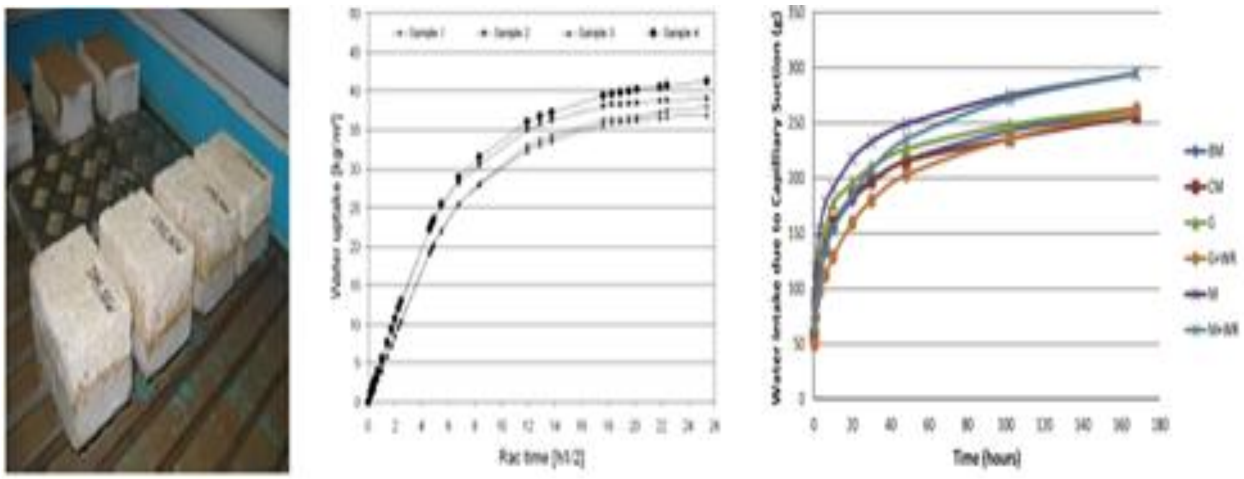
In the other study by Evard (2006), “b” was found as 2.73 $\%/\%_{mass}$ for (density 361- 466kg/m3), assuming a linear relationship between thermal conductivity and water content.

3.6.2.5 Liquid Absorption Coefficient (A Value)

The water uptake coefficient is a measure of the water sorption as a function of the surface area of the specimen and time (Walker & Pavia, 2014). The liquid transfer coefficient (A) is the slope of the mass uptake curve and is proportional to the square root of time (√h, or √s) during 24 hours (Evard, 2008).
According to Mensinga (2009), A-Value= (σ/SA) x1000
Where, A-value= Water uptake coefficient (kg/m2 $s^{-1/2}$), σ = Initial slope (kg/$s^{1/2}$) and
SA= Surface area (m^2)

For Water absorption (uptake) coefficient (A Value), Walker & Pavia (2014) placed the samples on a wire grill (EN1925:199) in a container of water so that the water covered the lower 10 mm of the samples and weighted at intervals over time for the duration of the test 10,000 min. According to Figure 18i below, the water sorption coefficient (A value) varied between 2.65 to 3.37 kg/m2 $h^{-1/2}$ (0.044 to 0.056 kg/m2 $s^{-1/2}$) over the first 24 h for densities 531-627kg/m3.

However, Evard (2008) measured during 24h following DIN 52 617 (EN ISO 15148) by placing samples in 5mm of water (lateral side protected with paraffin). Mass measurements were performed respectively after: 1min, 5min, 10min, 30min, 1h, 2h, 3h, 4h, 5h, 6h, 21h, 22h30, 23h, 24h... Mass uptake appears linear for the first 24h (Figure 18ii). Water absorption coefficient of hempcrete wall was found as 4.42 ± 0,27 kg/m2 $h^{-1/2}$ = 0.074 ± 0.005 kg/m2 $s^{-1/2}$ for density 440 kg/m3.



i. (Evard, 2008) in 5mm water ii. (Walker & Pavia, 2014) in 10mm water

Figure 18: A-value measurement in 5mm and 10mm of water

However, de Bruijn et al (2009) found A-value as 9 kg/m2 $h^{-1/2}$ (0.15 kg/m2 $s^{-1/2}$) for high density (587-733kg/m3) hempcrete. As it can be seen from the capillary behavior of hempcrete (Figure 18), water absorption is initially high, decreasing as time progresses.

3.6.2.6 Saturation Coefficient

The saturation coefficient is a measure of the quantity of open pore space available under average wetting conditions. The lower the coefficient of saturation, the more space is available to accommodate expansion of liquid water as it freezes (Mensinga, 2009).

Saturation Coefficient is defined as the ratio of free water saturation (W_f) to maximum water content (W_{max}) (ASTM C62).

In the study of Evard (2008) and Evard & De Herde (2005) for the hempcrete wall (hemp to binder: 1:2, dry densities 440 kg/m3 and 480kg/m3), saturation coefficients found were 0.75 and 0.84 respectively.

3.7 Discussion on Literature Review

Following findings were observed from literature review regarding hempcrete. Table 6 below highlights the reference values of the hempcrete properties.

S. No	Properties	Unit	(Min- Max)	General Range
1	**Dry Density (ρ_0)**	kg/m3	220[1]-627[2]	300-500(Wall)
2	**Porosity (Φ)** (W_{max}/ρ_{water})	m3/m3	0.71[(3,4)]-0.84[5]	0.71-0.73
3	**Dry Thermal Capacity (c_0)**	J/kgK	1000[(6,7)]-1700[8]	1500-1600
4	**Dry Thermal Conductivity (k_0)**	W/mK	0.06[(1,9)]-0.13[5]	0.06-0.12
5	**Dry Vapor Diffusion Resistance Factor (μ_0)** Sd=μd, δ_0= (δ_a / μ_0)	(-)	3.59[10]-7.68[10]	4.84-4.85
6	**Moisture Buffer Value (MBV)** [($\Delta m/A(RH_{high}-RH_{low})$)]	g/(m^2 %RH)	2.11[11]-2.14[6]	2.11-2.14
7	**Thermal Diffusivity (α)** (k_0 / $\rho_0 c_0$)	m2/s	(1.48[4] -1.68[11])10^{-7}	(1.48 -1.68) x10^{-7}
8	**Thermal Effusivity (Eff)** $(\rho_0 c_0\ k_0)^{1/2}$	J/m2K$s^{-1/2}$	286[4]-297[11]	286-297
9	**Dampening**	%	98.5[4]	98.5
		Time Shift	15[4]	15
10	**Air Tightness**	m^3/hm^2@ 50 Pa	1.2[12]-2.0[13]	1.2-2.0
11	**Fire Safety**	hr	1.22[12]-1.67[13]	1.22-1.67
12	**Free Water Saturation (W_f)**	kg/m3	546[11]-596[4] (124%mass)	124%mass
13	**WC at 80% RH ($MC_{80\%\ Equiv}$)**	kg/m3	33[11]-36[4] (7.5%mass)	7.5%mass
14	**Maximum WC (W_{max})** ($\Phi x \rho_{water}$)	kg/m3	711[(3,4)]-843[5]	166%mass
15	**Thermal Conductivity Supplement (b)** [ρ_0 (k-k_0)/k_0 w)]	%/%mass	2.73[10]-3.34[11]	3.34
16	**Liquid Absorption Coefficient (A- Value)** [(σ/SA) x1000)]	kg/m2 $s^{-1/2}$	0.044[2]-0.15[14]	0.074
17	**Saturation Coefficient** (W_f/W_{max})	(-)	0.75[11]-0.84[4]	0.75-0.84
18	**Carbon Sequestration**	kgCO_2/m3	(-)108[13] - (-)133[15]	(-)108 - (-)133
19	**Compressive Strength**	MPa	0.05[1]-3.5[16]	0.05-0.35
20	**R value**	Imperial	R2[(12,17,18)]-3[19]/inch	R2-2.5/inch

Table 6: Properties of Hempcrete

1. Cerezo (as cited in Lawrence et al, 2012), 2. Walker & Pavia (2014), 3. Mawditt (2008)
4. Evard & De Herde (2005), 5. Collet & Pretot (2014), 6. Collet et al (2013), 7. Tran Le et al (2010)
8. Abbott (2014), 9. Arnaud & Gourlay (2012), 10. Evard (2006), 11. Evard (2008)
12.Stanwix & Sparrow (2014), 13. Bevan and Woolley (2008), 14. de Bruijn et al (2009)
15. Eberlin & Jankovic (2015), 16.Lanos and Collet (2011), 17. Magwood (2013),
18. Alembic Studio, LLC (2013), 19. Maher (2014)

Based on the literature review, it can be concluded that hempcrete has the properties of good thermal insulation, excellent moisture buffering, thermal mass (heat storage), low thermal diffusivity and effusivity, phase change property, high dampening with longer time shifts, high comfort, low maintainability, low thermal bridging, biodegradable, good indoor air quality (ventilation), fire resistance and high carbon sequestration.

It is usually used in a composite (timber frame) structure because of low compressive strength. Currently there are no set standards for hempcrete; however, to some extent, some manufacturers/suppliers have established basic details/standards. In the context, extensive literatures review, laboratory experiments and research are going on. Canada, although grows ample quantity of hemp but hempcrete construction in Canada is in handful numbers.

Hygroscopic region of hempcrete extends up to 93%RH (normal range for others 40-70%) and this small additional amount of moisture in the hemcrete plays an important role in its thermal performance due to phase change. R-value of hempcrete wall is expected to be in between R2.0 to R2.5 per inch and the ideal wall thickness for hempcrete would be 250-300mm. While comparing hempcrete with other sustainable materials such as straw bale, brick and mud brick, its performance on all the parameters (thermal comfort, construction cost, workability, fire resistance, density, embodied energy, carbon footprint and recycling) are also commendable. Finally, the studied hempcrete case buildings are also found functioning well, as anticipated.

4.0 Research Methodology and Limitations

4.1 Research Methodology

The research methodology was comprised with four major actions: literature review, laboratory testing and analysis, identifying hempcrete wall thickness to meet OBC requirements and hygrotheral analysis of wall through WUFI modelling and sensitivity analysis.

To comprehend the impact on the properties of hempcrete with increasing lime binder, 3 types of mixes were studied: Mix 1 (Lime to binder ratio 1:1), Mix 2 (Lime to binder ratio 1:1.5) and Mix 3 (Lime to binder ratio 1:2) with almost same proportion of water input. As referred in the Table 7, Mix 1 is typically used for roof where insulation is more important than strength and Mix 2 and Mix 3 are used for wall to balance both insulation and structural integrity.

Application	Shiv: Binder Proportion (by mass)	Target Density (kg/m3)	Typical Ultimate Compressive Strength (N/mm2)	Typical Thermal Conductivity (k) (W/mK)
Roof Insulation	1:1	220	0.05	0.06
Wall Construction	1:1.5	275	0.11	0.06-0.09
Wall Construction	1:2	330	0.22	0.09-0.115
Wall Construction (Compressed)	1:2	440	0.35	0.115
Floor	1:3	500	0.8	0.13
Floor	1:4	600	1.15	0.14
Precast Structural (Compressed)	1:4	600-1000	2-6	0.14-0.27

Table 7: Applications of hempcrete

(Lawrence et al, 2012)

4.1.1 Literature review

Relevant literatures such as books, articles, dissertations, research papers from scholarly journals, proceeding papers, codes and standards, manuals etc. were reviewed in depth- (i) to understand the hempcrete, its ingredients, mixing processes, applications, benefits, LCA, current performance of existing hempcrete buildings, performance of hempcrete over other sustainable building materials (strawbale, mud brick, clay brick), R values of hempcrete, mechanical and hygrothermal parameters etc. and (ii) to acquire best appropriate reference values of its properties to utilize in WUFI modelling. The findings of the literature review were highlighted in the previous chapter.

4.1.2 Laboratory testing and analysis

In order to understand the influence of binder in the properties of hempcrete and to increase the probable accuracy of the WUFI simulation as compared to utilizing all the literature inputs, several tests were conducted for different parameters. The entire tests were carried out after 26 days of natural drying where minimum density was stabilized.

Tests were carried out for all 3 mixes according to ASTM standards. Dry density (kg/m3), maximum water content (kg/m3), porosity (m3/m3) and free water saturation (kg/m3) were measured in accordance with ASTM C67-14 (Standard Test Methods for Sampling and Testing Brick and Structural Clay Tile) and saturation coefficient was defined by using ASTM C62-13a [Standard Specification for Building Brick (Solid Masonry Units Made from Clay or Shale)]. Since there was no specific test standard available for hempcrete, standards available for brick were utilized to conduct these tests.

Once the measurements were obtained from the tests and utilized in the calculation (in Excel sheet), they were represented graphically and/or in tabulation form and analyzed thoroughly.

4.1.3 Defining wall thickness according to OBC requirements

On the basis of most reliable reference R values, minimum thickness of wall required to meet the current OBC requirements were calculated in Excel sheet. This later represented in tabulation form and discussed.

4.1.4 Hygrothermal analysis of wall in WUFI software

To understand the heat and moisture transfer behavior of hempcrete wall, one-dimensional transient hygrothermal analysis for Mix 3, 300mm wall was conducted in WUFI Pro 5.3 software. Simulations were done for two types of wall assemblies; with or without sun, rain and wind exposure:

1. Assembly 1: Lime render (20mm) + Hempcrete (300mm) + Lime plaster (15mm); Total thickness: 335mm

2. Assembly 2: Wood cladding (spruce) (20mm) + Vented air layer (20mm) + Typar + Hempcrete (300mm) + Lime plaster (15mm); Total thickness: 355mm (rain screen system)

Reasons behind selecting Mix 3 wall (hemp to binder ratio 1:2) were to balance both structural integrity and insulation of wall and availability of reliable reference material data. Similarly, 300mm thick wall was considered to be ideal to meet OBC requirements.

WUFI doesn't contain materials data for hempcrete; hence, a new database was introduced for hempcrete by using both the test values and best appropriate reference values. Similarly, for Typar too, a new database was formed based on its literature. However, for lime render, lime plaster, wood cladding (spruce) and air layer, WUFI default material database were used (lime stucco for render and plaster).

Many assumptions such as no relevancy of temperature in moisture sorption, no air infiltration (user defined air-related moisture), no natural or forced convection, no stack effect, no volumetric variations (swelling and shrinkage) in samples, no any chemical reactions between water etc. were made to simplify the model. Boundary conditions such as Southeast orientation (to maximize the combination of sun exposure and rain waiting), exterior weather conditions with sun, rain, wind, cloud etc, interior environment with 21 ± 1^{0}C, RH 50±10%, no surface coatings etc. were included. Regarding sources and sink, for air layer (vented) - Assembly 2, constant air change source of 8/hr was introduced. Default WUFI climate file for Toronto, cold year was used for simulation. Outdoor climate was based on default weather file and user defined sine curve was used for indoor climate. Simulation was conducted for 3 years period.

Once the simulations were completed, results were exported in Excel sheet and all the parameters related to heat and moisture (temperature, RH, WC, Isopleths, dew point, film, profiles) at monitoring positions were represented graphically and/or in tabulation form and analyzed thoroughly for both the wall assemblies. In addition, comparative analysis between two assemblies (assembly 1 and assembly 2) was also done to understand the hygrothermal behavior of assemblies with and without sun, rain and wind exposure situations. Aside, series of sensitivity analysis for assembly 1 using reference values (moisture related and thermal conductivity- dry and moist state) was also carried out to identify the influence of such references.

Finally, based on the analysis; findings, conclusion and recommendations were made.

4.2 Limitations

This study was purely for an academic purpose and it had limitations of both time and laboratory test data. Many material inputs were adopted from references and many assumptions were made during WUFI simulations; therefore, it may not have covered the entire gamut of a detailed research. As far as possible, all the above stated aspects were analyzed thoroughly to acquire effective results.

5.0 Laboratory Experiments

Laboratory activities such as mould making, batching, mixing, placing, natural drying, oven drying, 5 hours boiling test and 24 hours cold water submersion test were performed to measure dry density (ρ_0) (kg/m3), maximum water content (W_{max}) (kg/m3), porosity (Φ) (m3/m3), free water saturation (W_f) (kg/m3) and saturation coefficient (-). Following sections highlight detail activities and results on laboratory experiment.

5.1 Samples Processing

5.1.1 Sources of Raw Materials

5.1.1.1 Lime Binder

St. Astier Natural Hydraulic Lime's hemp construction pre-formulated product "BATICHANVRE" was used in research (Figure 19). It is a proprietary binder and supposed to be in the mix of: majority of air (hydrated) lime+ possibly a small portion of pozzolanic ingredients+ about 20-30% of Portland cement (Stanwix & Sparrow, 2014). This lays setting process as mixture of both carbonation (exposure to air) and hydraulic (exposure to water) set.

Density: 711.86kg/m3 (Measured in Lab)

Lime Binder Hemp Particles

Figure 19: Raw materials

5.1.1.2 Hemp

Hemp Hurd (without fiber or dust) was sourced from Canadian grown and processed from plain hemps in Manitoba (Figure 19); particle sizes ranging from- length: 0.5 cm to 2.5 cm (¼" to 1"), width: 3mm to 6mm (2/16" to 4/16"), thickness: 1.5mm to 2.5mm (1/16" to 1.5/16") and density: 125.42 kg/m3 (measured in Lab).

5.1.2 Batching

Batching of components was followed (for 3 mixes) according to binder producer's and reference literatures (Table 8 and Figure 20).

Mix	Mass Batching				
	Hemp (g)	Binder (g)	Water (g)	Proportions	
				Hemp to Binder	Binder to Water
1	5030.00	5012.00	8000.00	1:1	1:1.6
2	4994.00	7502.00	10500.00	1:1.5	1:1.4
3	4010.00	8002.00	11000.00	1: 2	1:1.37

Table 8: Batching for different mixes

5.1.3. Mixing and Casting

For mixing, mechanical bell (drum) mixer was used (Figure 20). By following the "BATICHANVRE" literature; water (partial) and binder was mixed first for about 5 minutes, then hemp and remaining water was mixed gradually for another 5 minutes. Total mixing time was about 10 minutes.

Batching

Mixing in Bell Mixer

Figure 20: Batching and Mixing

Mix was neither violent nor too long, so no hemp particles were damaged. Implementation of the samples in the mould was made very close to the mixer. The samples were manually filled, lightly pressed by hand (light compaction) avoiding “arching” or empty zone.

Components	Mix					
	1		2		3	
	Mass	%Mass	Mass	%Mass	Mass	%Mass
Hemp	1	28%	1	22%	1	17%
Binder	1	28%	1.5	33%	2	35%
Water	1.6	44%	2.1	46%	2.75	48%
Total=	3.6	100%	4.6	100%	5.75	100%

Table 9: Mix proportions by mass

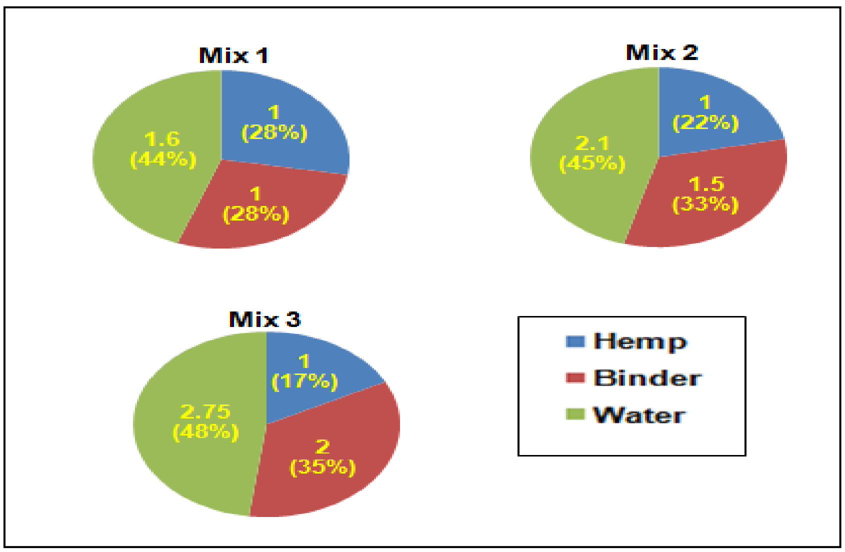


Figure 21: Mix Proportions

Ball and Finger test

Final Product

Figure 22: Ball and Finger test and Final product

Mixing (Table 9 and Figure 21) was done in room temperature 20-21^{0}C and RH ≈ 50%. Total hempcrete casted was 0. 0301m3 (1.06 cft) x 3 mixes= 0.0903m3 (3.18cft). To confirm consistancy of mix, as suggested by Stanwix and Sparrow (2014), ball and finger tests (squeezing some hempcrete into a ball and pushing it by a finger) was conducted for all mixes before placing in moulds (Figure 22). In Mix 1, it was slightly crumbled (because of low binder proportion) but in others (Mix 2 and Mix 3), it was perfect (splitted into two). In overall, final product (Figure 22) was in fully satisfactory state.

5.1.4 Sample Sizes

Four types (18 numbers, 6 for each mix) of samples were casted in plywood mould. In order to get precise results, variation in sample sizes was made. Numbers and sizes of samples casted are highlighted in below table (Table 10).

Mix	Samples				Total
	Type 1		Type 2,3,4		
	Size(cm)	Number	Size(cm)	Number	
1	30.50x30.50x7.62	3	15.24x15.24x15.24	1	6
			15.24x15.24x12.70	1	
			15.24x15.24x10.16	1	
2	30.50x30.50x7.62	3	15.24x15.24x15.24	1	6
			15.24x15.24x12.70	1	
			15.24x15.24x10.16	1	
3	30.50x30.50x7.62	3	15.24x15.24x15.24	1	6
			15.24x15.24x12.70	1	
			15.24x15.24x10.16	1	

Table 10: Original Samples

5.2 Drying

Once filled, the samples were placed in a typical inside condition (about 50-60% RH, 20- 21°C temperature) for drying (Figure 23) and their mass m(g) was measured with an electronic weighing scale (Figure 24) once a day, for 26 days. Based on this mass, mean density was calculated in reference to mould volume [ρ (t)= m(t) / V_{mould}]. Evolution of density with time is illustrated in Figure 25. Bulk volume V (m^3) was measured for all samples after oven dried. Shrinkage or swelling (V_{mould}/V_0) , as mentioned earlier was not considered in the study. Volume of the samples were defined with Digital Caliper 0-150mm (Macrometer) scale (Figure 24) . However, displacement (inserting samples in the vessel and defining volume) method too was tried. But it couldn’t become successful due to drifting of samples above water (density of samples was less than water).

Samples were removed from the mould in day 6 and wrapped with aluminum foil (Figure 23) from three sides (one side opened, allowing drying and carbonation simultaneously). During these activities, moulds were weighed once again and noticed that mould weight in average was increased by 2.89% (water absorbed). It was due to water absorption by moulds (plywood). It was considered that the increment was from day 1, thus net mass and density from day 1 to day 5 were calculated based on increased mould mass.

Figure 23: Samples in mould and aluminum foil during drying

Weighing Scale Caliper Scale Temperature Gun

Figure 24: Instruments used for test

The density/mass was stablized during drying/carbonation in day 26 (below 1% variation of preceding day density) (Figure 25).

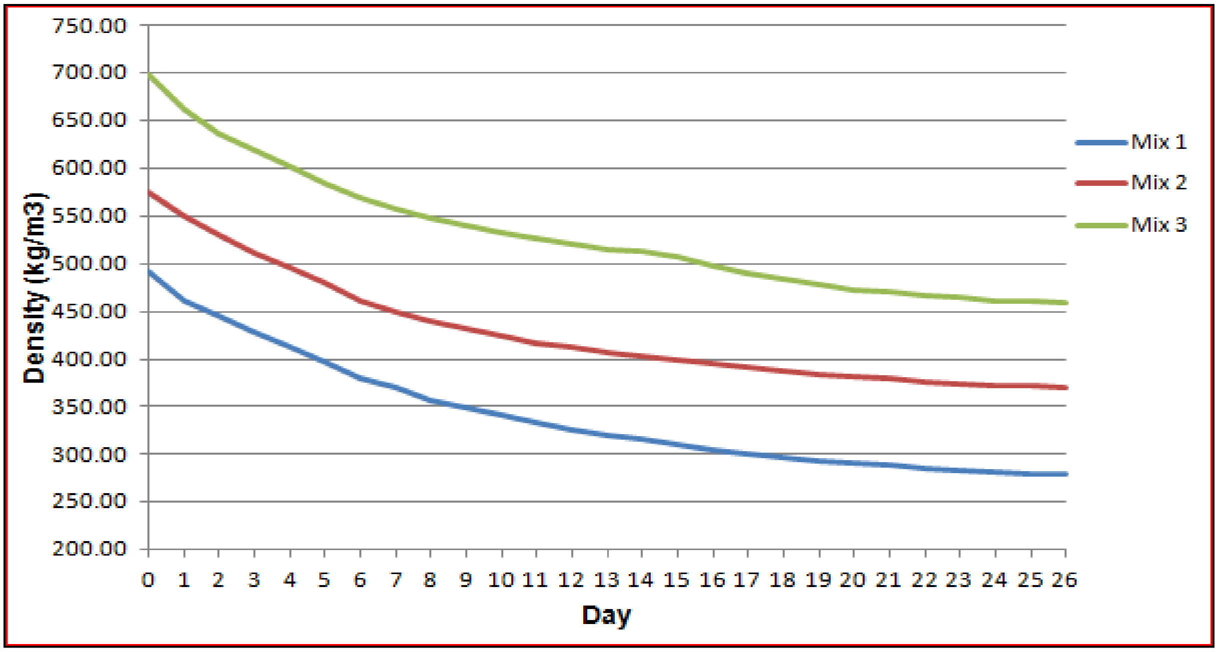


Figure 25: Evolution of Density during Natural Drying

Initial densities (Day 0) for mixes were 491.89 kg/m3 (mix 1), 574.37 kg/m3 (mix 2) and 697.76 kg/m3 (mix 3). Minimum densities(day 26) obtained during natural drying were 279.12kg/m3 (-43.26%), 374.42kg/m3 (-34.81%) and 464.00kg/m3 (-33.50%) respectively for Mix1, Mix 2 and Mix 3 (Table 11). The above mentioned densities were the average of the 6 different samples for each mix.

5.3 Experiment: Implementations, Results, Observation and Discussion

All the original block samples (15.24x15.24x15.24 cm, 15.24x15.24x12.70 cm and 15.24x15.24x10.16 cm) were then cut into 36 cubes (12 for each mix) with edges 7.62cmx7.62cmx7.62cm (3"x3"x3") (volume 442.45cm3) (Figure 26). Their sizes were embedding the representative volume of the material (RVE). According to visual analysis of Evard (2008) regarding representative volume element (RVE) of hempcrete, the specimens larger than 100 cm3 (sides >4.7 cm) can take into account the specific pore and particle distribution of the material (Collet et al, 2013). 9 original samples (3 for each mix) of size 30.4x30.4x7.6 cm were never cut down.

Figure 26: Cut Samples

5.3.1 Dry Density (ρ_0)

The samples (45 numbers -15 for each mix) were dried in oven (Figure 27) for 24 hours at 110^{0}C until two successive weighing at intervals of 2 h show an increment of loss not greater than 0.2 % of the last previously determined mass of the specimen.

Figure 27: Oven Drying

Dry densities were measured according to ASTM C 67 (drying was followed by cooling for a period of about 12 hours until the surface temperature of the samples was within ± 2.8^{0}C of room temperature) and found as 233.03kg/m3 (Mix 1), 316.79kg/m3 (Mix 2) and 387.84kg/m3 (Mix 3) (Figure 28, Table 11). To measure surface temperature, Laser Temp Gun Thermometer (Milwaukee) was used (Figure 24).

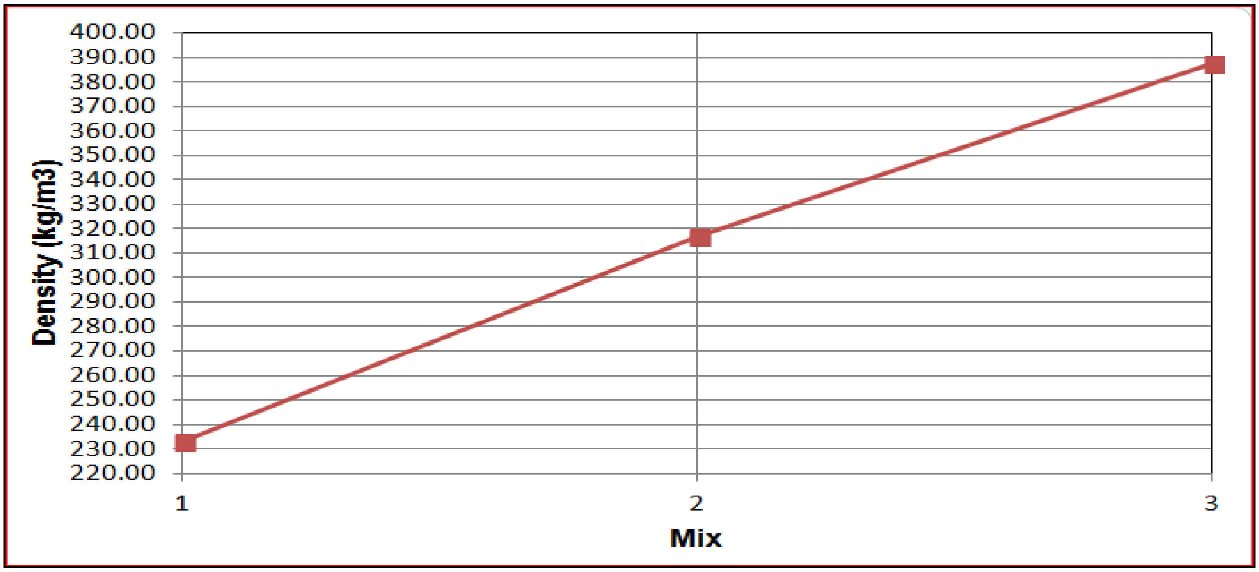


Figure 28: Dry Densities of different mixes

It is interesting to know (Figure 28) that the measurements of dry density were in almost linear mode with proportion to binder. When binder was increased by 50%, density was increased by 36% and when binder was increased by 100%, density was increased by 67%. From this it can be depicted that proportion of increment of density goes almost linearly with respect to addition in binder.

Mix	Density (kg/m3)			Initial to Natural Drying	Initial to Oven Dry	Natural Drying to Oven Dry	Dry Density (in reference to)	
	Initial	Natural Drying	Oven Dry				Mix 1	Mix 2
1	491.89	279.12	233.03	-43.26%	-52.63%	-9.37%		
2	574.37	370.50	316.79	-35.50%	-44.85%	-9.35%	35.94%	
3	697.76	459.89	387.74	-34.09%	-44.43%	-10.34%	66.39%	22.40%

Table 11: Variation in densities

As shown in the above table (Table 11), density reduction during drying in average was about 40% (Mix 1 was decreased by 43%, the highest of all because of more added water during mixing). After natural drying to oven dry, reduction was just about 10% (in average). In overall, decrease in density from initial to oven dry was: Mix1 ≈53%, Mix2 and Mix 3≈45%. However, our obtained densities were within the satisfactory range of references and were utilized in WUFI.

5.3.2 Free Water Saturation (W_f)

Free water saturation (W_f) was measured according to ASTM C67. To measure W_f, immediately after measuring the dry densities, the samples (15 random cut samples - 5 for each mix) were submerged into the cold clean water (Figure 29) at 15.5 to 30^{0}C temperature for 48 hours (until mass equilibrium of 1% variance was achieved) and was weighed periodically (measuring scale was sensitive to 1g). Weighing was completed within 5 minutes after removing the specimen from the bath and wipping off the surface water with a damp cloth. During submersion, over the samples plywood pieces were put to fully submerse it, otherwise it was drifting. Free water saturations (W_f) for the mixes measured were - Mix 1: 376.29kg/m3 (161.48%mass), Mix 2: 374.96kg/m3 (118.36%mass) and Mix 3: 423.55kg/m3 (109.24%mass) (Table 12).

Cold Water Submersion

5 Hours Boiling

Figure 29: Boiling and submersion

5.3.3 Maximum Water Content (W_{max})

To get W_{max}, there were two methods mentioned in ASTM C67; either by immediately using the same cold water submerged samples to boiling for 5 hours or first dry the samples then boiling for 5 hours. For authentication both the methods were applied.

The samples were submerged in clean water at 15.5 to 30^{0}C in a manner that water circulated freely on all sides of the samples. Then heated water to boiling, within 1 hour and heated continuously for 5 hours (Figure 29). After 5 hours of boiling (over the samples plywood pieces were put to fully submerse it), samples were allowed to cool to about 25^{0}C by natural loss of heat for 48 hours . Although ASTM doesn't say about cooling time but according to Mensinga

(2009), as per CSA it should be cooled for minimum 12 hours and maximum 72 hours. In both the cases W_{max} (48 hours) found was almost identical. It was to be noted that during both the boiling and cold water submersion, no samples were crumbled or exfoliating. The boiling test was conducted at author's residence. Maximum Water Content at saturation (W_{Max}) for the mix measured were - Mix 1: 532.66kg/m3 (228.58%mass), Mix 2: 525.66kg/m3 (165.93%mass) and Mix 3: 655.31kg/m3 (169.01%mass) (Table 12).

5.3.4 Porosity (Φ) and Saturation Coefficient

Based on the values of W_{max}, porosity was measured as $\Phi = W_{max} / \rho_{water}$ and found 0.53m3/m3 (53% volume) for mix 1 and mix 2 and 0.66m3/m3 (66% volume) for mix 3 (Table 12).

Similarly, saturation coefficient was measured based on W_f / W_{max} (ASTM C62-13a) and found as 0.71(mix 1 and mix 2) and 0.65 (mix 3) (Table 12). From these findings, it can be concluded that mix 3 has lower coefficient of saturation, hence it has more space available to accommodate expansion of liquid water as it freezes in comparison to mix 1 and mix 2. Below (Figure 30) shows the pore structure of mixes in dry condition.

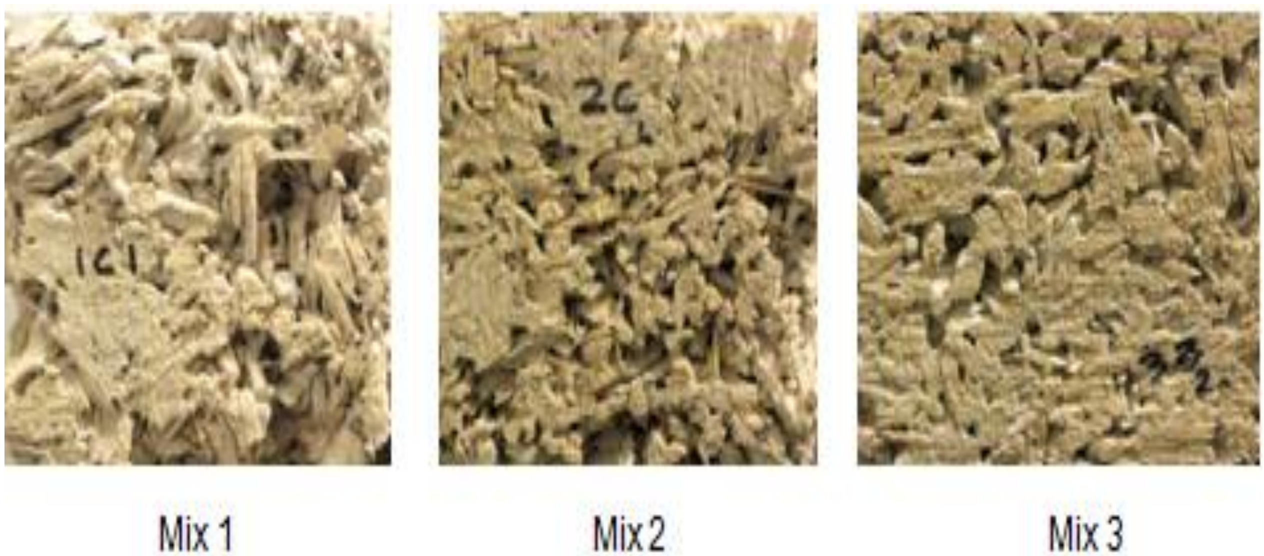


Figure 30: The pore structure of hempcrete

Below table (Table 12) summarizes all the water content parameters of the test.

Mix	Dry Density (kg/m3)	W_f (kg/m3)	W_{max} (kg/m3)	Absorption		Saturation Coefficient	Porosity (m3/m3)
				Cold Water (% Mass)	5 Hour Boil (% Mass)		
1	233.03	376.29	532.66	161.48%	228.58%	0.71	0.53
2	316.79	374.96	525.66	118.36%	165.93%	0.71	0.53
3	387.74	423.55	655.31	109.24%	169.01%	0.65	0.66

Table 12: Different features of water content

In compare to references, values of W_f, W_{max}, saturation coefficient and porosity (Φ) in our case were slightly less; however, (%) mass were almost similar. Since in reference, W_f, W_{max} and Φ were measured through dynamic test, our results can't be considered as 100% precise. Hence, a sensitivity analysis was conducted in WUFI for reference values (moisture related) to compare the simulation outputs.

5.3.5 Summary of test results

Following table (Table 13) highlights the summary of overall test measurements.

Mix	Dry Density (kg/m3)	Porosity (m3/m3)	W_f (kg/m3)	W_{max} (kg/m3)	Saturation Coefficient
1	233.03	0.53	376.29	532.66	0.71
2	316.79	0.53	374.96	525.66	0.71
3	387.74	0.66	423.55	655.31	0.65

Table 13: Summary of test results

(For detail laboratory test results see Appendix C)

6.0 Minimum wall thickness required to comply OBC

6.1 OBC Requirements

Among the applicable 3 perspective compliance packages in OBC Supplementary Standard SB-12, subsection 2.1.1 (Space heating equipment with AFUE ≥ 90%, Space heating equipment with AFUE ≥ 78% and < 90% and Electric Space Heating), building using space heating equipment with annual fuel utilization efficiency (AFUE) ≥ 90% for Zone 1 (< 5000 heating degree days) was chosen for this study (Table 14). Within this package, for thermal insulation of the exposed above grade walls, there are 13 compliance packages (A-M) with minimum "R" value ranging from R-22 (RSI 3.87) to R-27 (RSI 4.75) [3 R values: R22, R24 and R27]. (For detail compliance package, see Appendix A).

Table 2.1.1.2.A Zone 1-Compliance Packages for Space Heating Equipment with AFUE ≥ 90% Forming Part of Sentence 2.1.1.2.(1)													
Component	Compliance Package												
	A	B	C	D	E	F	G	H	I	J	K	L	M
Walls Above Grade: Minimum RSI (R)-Value	4.23 (R24)	4.75 (R27)	4.75 (R27)	4.23 (R24)	4.23 (R24)	4.23 (R24)	4.23 (R24)	4.23 (R24)	3.87 (R22)	3.87 (R22)	3.87 (R22)	4.23 (R24)	4.23 (R24)

Table 14: Minimum R-Value required (OBC)

6.2 Minimum Wall thickness required (based on reference R values)

From literature review, it was noticed that Mix 2 and 3 were specifically used for wall purposes and the R value targeted/found for these mixes was between R2-2.5/inch. Based on this reference, following wall thicknesses (Table 15) were found to meet OBC requirements

R Value per Inch	Minimum wall thickness					
	For "R"-22		For "R"-24		For "R"-27	
	Inch	mm	Inch	mm	Inch	mm
2.0	11.0	279.4	12.0	304.8	13.5	342.9
2.5	8.8	223.5	9.6	243.8	10.8	274.3

Table 15: Minimum wall thickness required

Based on the above table (Table 15), it can be concluded that to meet the OBC requirements for thermal performance (R22-R27), minimum wall thickness required will be ≈250-300mm.

7.0 Hygrothermal Analysis in WUFI

WUFI doesn't contain materials data for hempcrete. Hence, to simulate the hempcrete in WUFI, material inputs were obtained from both the laboratory tests and the most appropriate references. A series (four) of sensitivity analysis for reference values (water sorption and range of "k" values in dry and moist state) was also carried out to identify the impact of such references.

7.1 Material Inputs

By using following inputs a hempcrete wall (base case) was introduced in the WUFI material database

Relative to dry state:

1. Dry density (ρ_0) = 388kg/m3 (test)
2. Dry Total porosity (Φ) = 0.66 m3/m3 (test)
3. Dry Specific heat capacity (c) = 1560 J/kg K (reference)
4. Dry Thermal conductivity (k) = 0.1 W/mK (reference)
5. Dry Water vapour diffusion resistance factor (μ) = 4.85 (reference)

Relative to moist state:

1. Thermal conductivity supplement (b) = 3.34 %/%mass (reference)
2. Water content at RH 80% ($WC_{80\%EQUIV}$) = 29 kg/m3 (7.5% mass) (test)
3. Water content at free saturation (W_f) = 424kg/m3 (test)
4. Maximum water content (W_{Max}) = 655kg/m3 (test)
5. Water absorption coefficient (A-value) = 0.074 kg/m2/s$^{1/2}$ (reference)
6. Typical Built-In (Initial) MC = 674kg/m3 (day 0 density)-388kg/m3 (Dry density) = 286kg/m3 (test)

7.2 Assumptions

Assumptions made to simplify the model were:

1. Samples - isotropic, homogenous and without volumetric variations (swelling and shrinkage neglected)
2. No any chemical reactions between water, in all the 3 phases
3. No energy dissipation during flows

4. No parameter has time dependency
5. No hysteresis (univalent relationship between water content and relative humidity)
6. No air infiltration (user defined air-related moisture)
7. No relevancy of temperature in moisture sorption
8. No natural or forced convection and no stack effect

7.3 Boundary conditions

Boundary conditions in one-dimensional hygrothermal analysis were included, but not limited to: exterior weather conditions (rain, sun, wind, cloud, temperature, relative humidity, etc.), interior environmental conditions (temperature, relative humidity), initial material moisture contents, etc.

1. Inside environment: 21 ±1^{0}C, RH 50±10%
2. Initial condition: 20^{0}C, 80% RH (constant across component)
3. Southeast orientation (to maximize the combination of sun exposure and rain waiting); Vertical surface [R1=0, R2= 0.07m/s; Short building- height up to 10m]
4. Heat transfer coefficients (h_i and h_e) : Program default (constant coefficient); h_i= 8.0W/m2K, h_e= 17.0W/m2K
5. Short-wave absorptivity a_s (limestone bright and spruce untreated) =0.4
6. Rain water absorption factor a_r = 0.7
7. No surface coatings
8. ACH- 8 for air layer (vented) for assembly 2
9. Cloud Index: 2.64 (as analyzed in weather file)
10. Simulation period: 3 years (10-1-2015 to 10-1-2018)
11. Others: Program Default

7.4 Climate File

Default WUFI climate file for Toronto, cold year was used for simulation. Values for outside temperature and RH were based on weather file. User defined sine curve was used to define the inside temperature and RH referring to classical inside environment in residential houses.

7.5 Modelled Wall Assemblies

Two types of wall assemblies (Figure 31) were modelled; with and without exposure of rain, wind and sun.

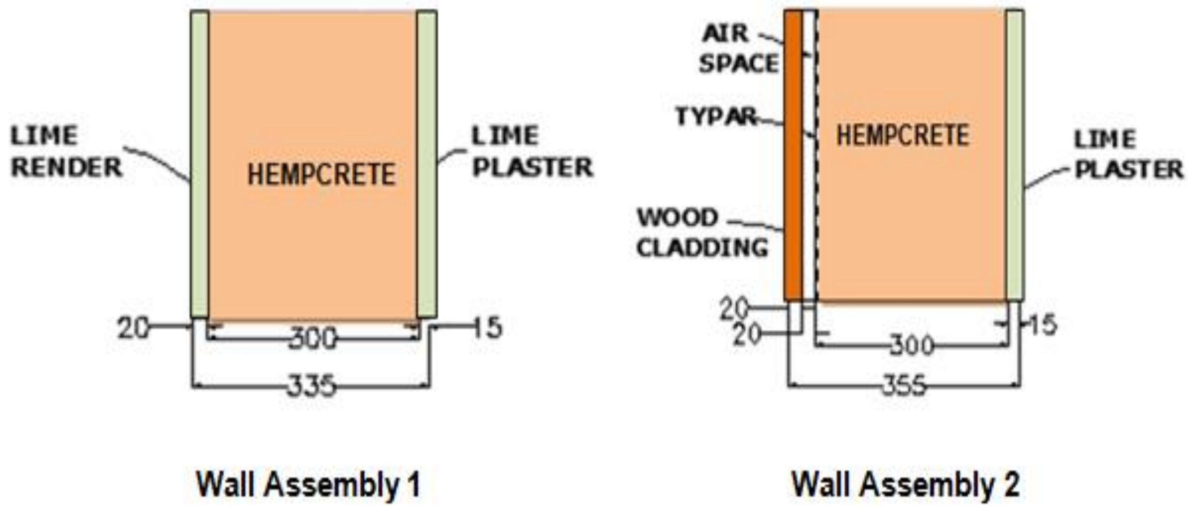


Figure 31: Wall Assemblies

1. **Assembly 1:** Lime render (20mm) + Hempcrete (300mm) + Lime plaster (15mm); Total thickness: 335mm
2. **Assembly 2:** Wood cladding (spruce) (20mm) + Air layer (20mm) + Typar + Hempcrete (300mm) + Lime plaster (15mm); Total thickness: 355mm (Rain Screen system)

(For Spruce, air layer and lime plaster, WUFI default material database were used; for Typar new database was created)

Regarding sources and sink, for vented air layer (assembly 2) constant air change source of 8/hr was introduced.

7.6 WUFI Simulations Outputs: Observations and Discussions

7.6.1 Wall Assembly 1 - Base Case

Hygrothermal aspects such as condensation risk, mold risk, freeze thaw and subflorescence (salt) risks were assessed below in detail.

7.6.1.1 Condensation Risk

Water content (total and individual layer) and dew points are the major indicators to understand the condensation risk in assembly.

7.6.1.1.1 Total Water Content

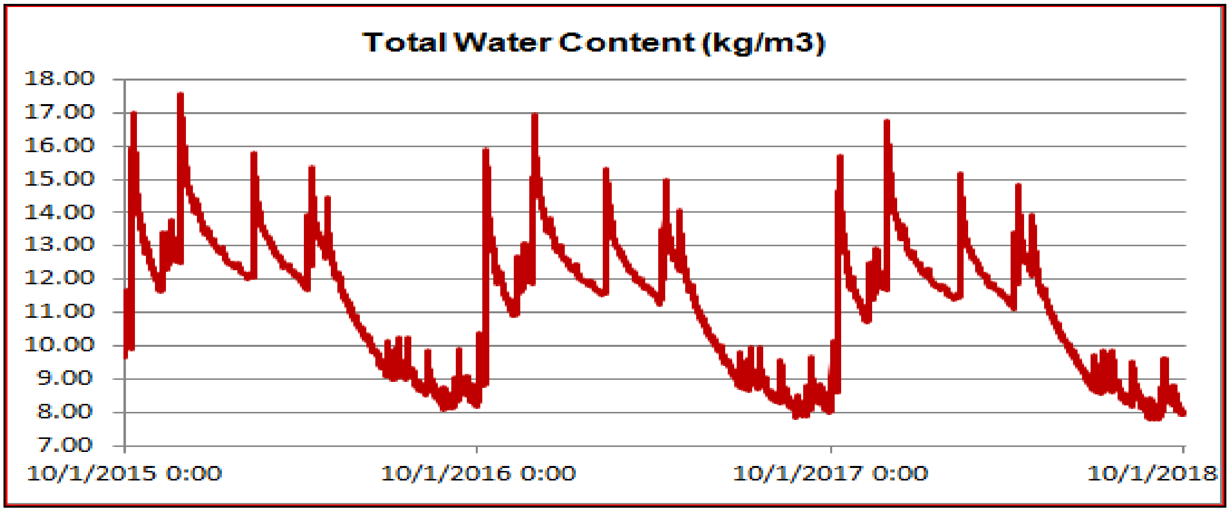


Figure 32: Total Water Content

Total WC has shown (Figure 32) a regular pattern of seasonal fluctuation and is decreasing over time. No long time accumulation of water at one point is observed and the range of total WC is very low (0.22-0.49%mass). The assembly is drying out continuously and hoping to reach in dynamic steady state soon under the applied climatic conditions.

7.6.1.1.2 Water Content in Individual Layer

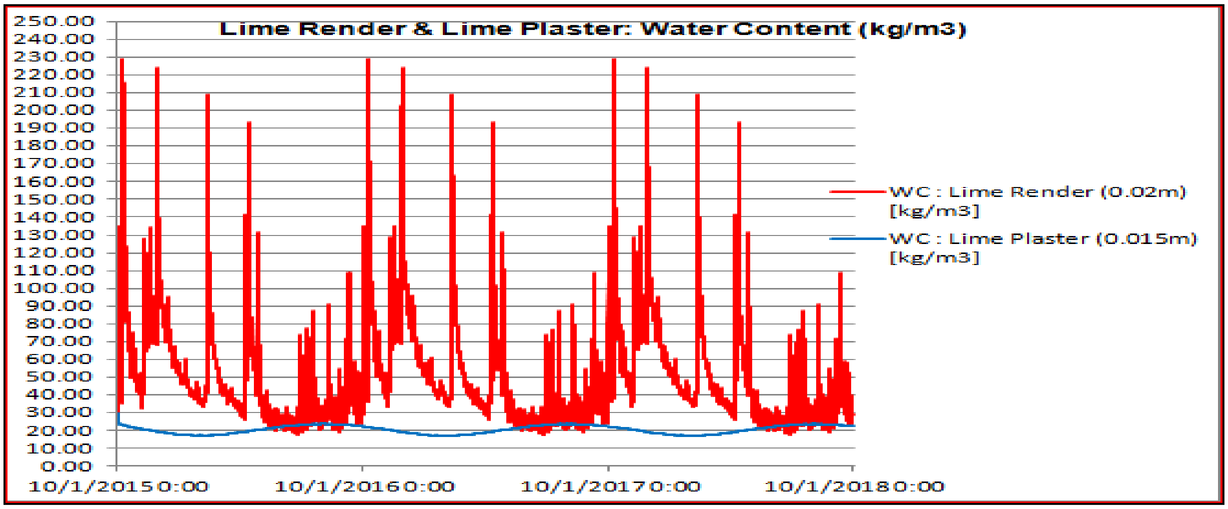


Figure 33: WC in Lime Render and Plaster

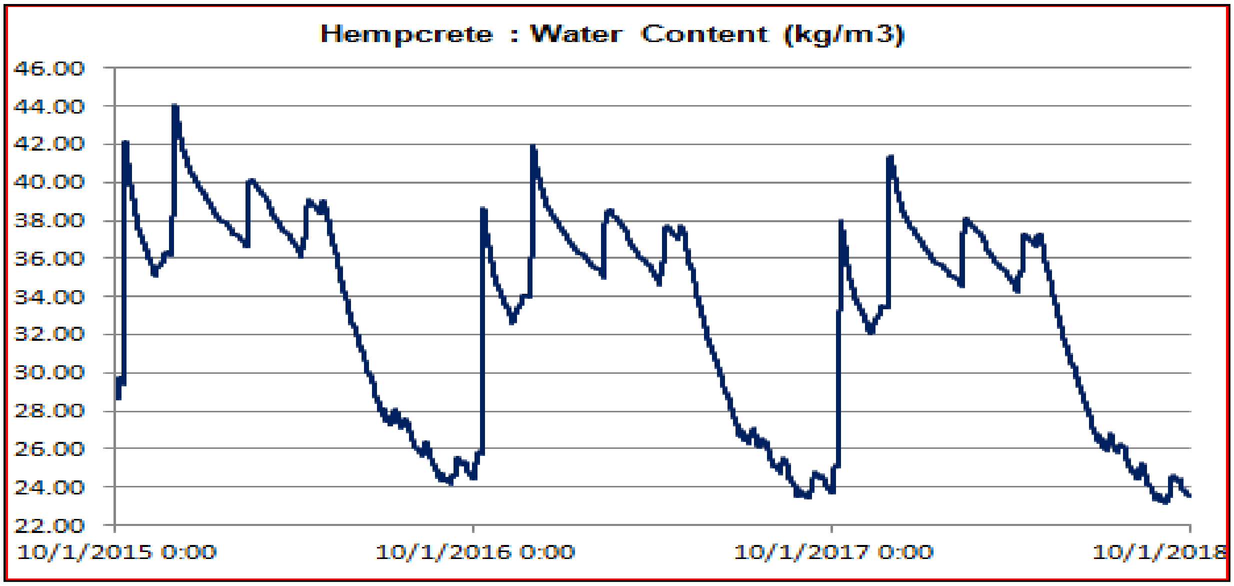


Figure 34: WC in Hempcrete

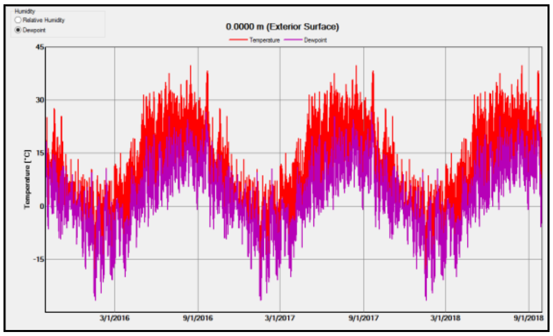
WC per individual layer has initially decreased (Figures 33-34) and thereafter established a regular pattern of seasonal fluctuation. WC in lime render and plaster has reached to dynamic equilibrium from the early cycles. However, WC in hempcrete is diminishing continuously, which indicates it is drying out fast and will reach in equilibrium soon. So far no moisture accumulation has seen occurred for long time in any individual layer and WC is less than 15%mass throughout the simulation period, considerably below the practiced standard (20%mass).Therefore, based on total and individual component WC evaluation, it can be depicted that the assembly shouldn't have any risk of condensation, rot or mould growth, reducing efficiency of insulation, subflorescence (salt effect) and freeze thaw damage.

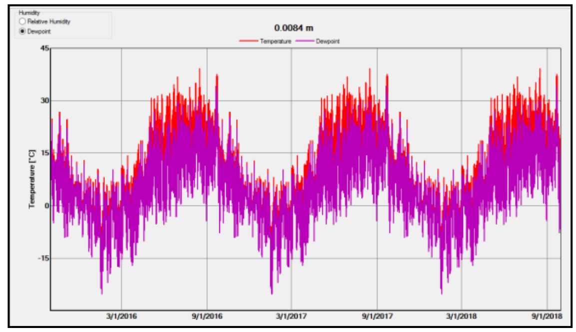
Below table (Table 16) summarize the range of total and individual layer WC during simulation period.

Water Content (kg/m3) (%Mass)			
Lime Render	**Hempcrete**	**Lime Plaster**	**Total**
17.95 -228.72 (1.12-14.30%M)	23.18- 44.07 (5.97-11.36%M)	17.06-30.00 (1.07-1.88%M)	7.78-17.57 (0.22-0.49%M)

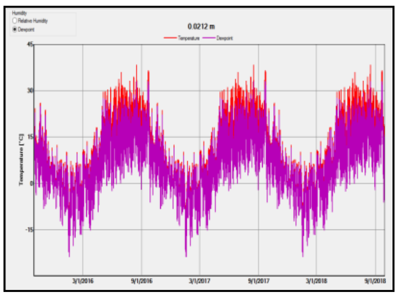
Table 16: Range of WC in assembly

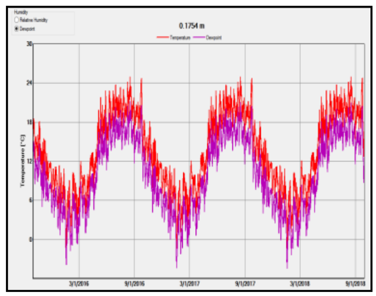
7.6.1.1.3 Dew Points

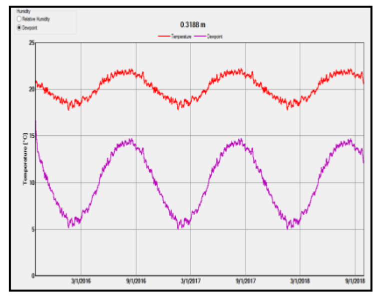




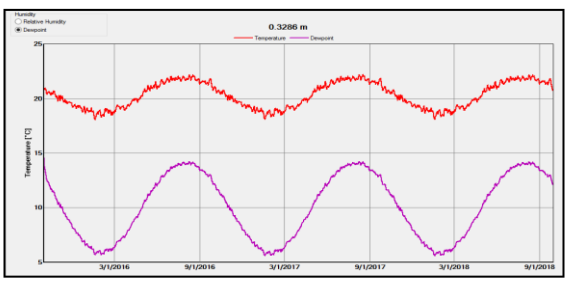
Lime Render- Exterior Surface (M-1) Middle (M-2)

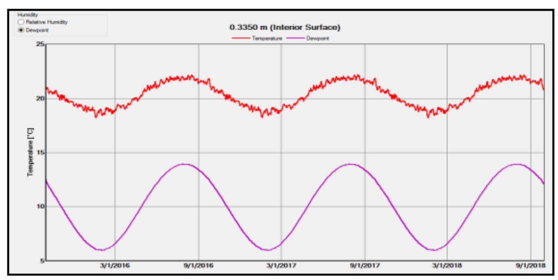






Hempcrete- Exterior (M-3) Middle (M-4) Interior (M-5)





Lime Plaster- Middle (M-6) Interior Surface (M-7)

Figure 35: Dew Points at Monitoring Positions

As in Figure 35, dew point at each monitoring position shows a regular pattern of seasonal fluctuation. However, up to the middle of hempcrete (monitoring positions 1-4), it is very close to temperature, but WC graph confirms that there is no evidence of water accumulation and condensation. At the monitoring positions 5-7 (interior surface) dew point falls considerably below the temperature. Therefore from both the factors (dew point and WC), no condensation risk is seen in the entire assembly.

7.6.1.2 Mold Risk

Mold risk is assessed through temperature and RH as well as Isopleths analysis.

7.6.1.2.1 Temperature and RH

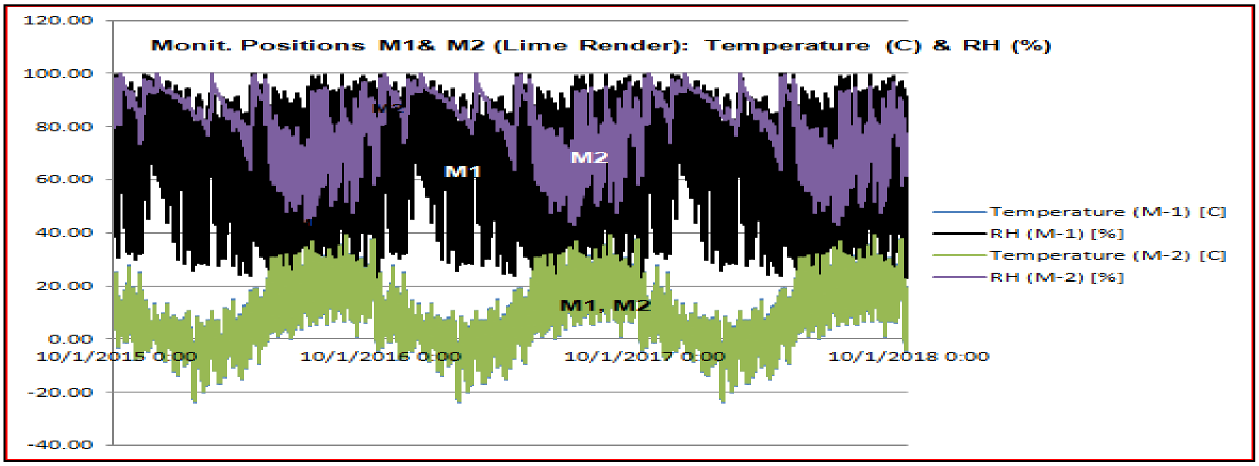


Figure 36: Lime Render- Exterior (M1) & Middle (M2): Temperature and RH

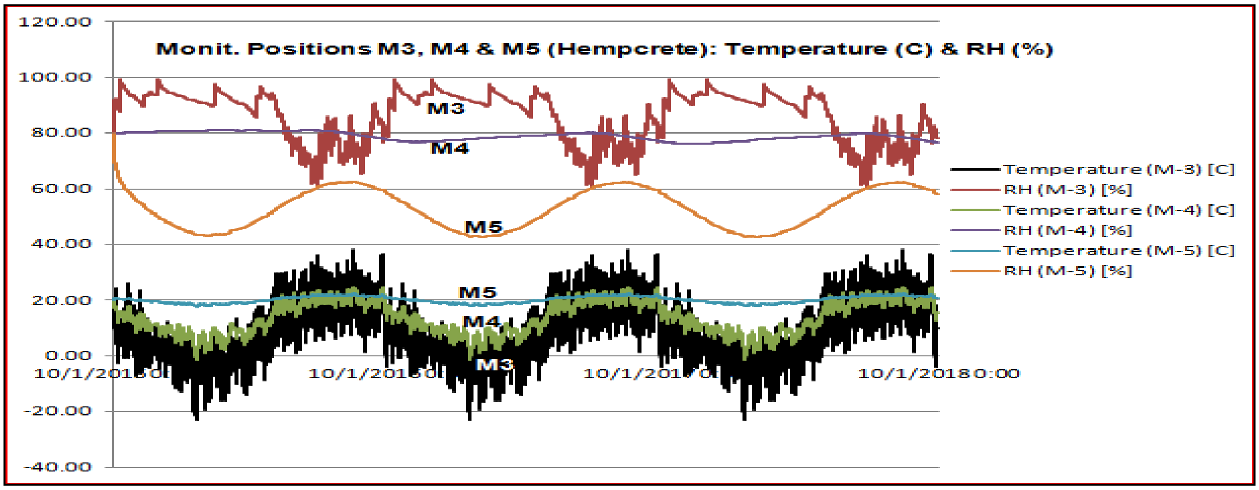


Figure 37: Hempcrete- Exterior (M3), Middle (M4) & Interior (M5): Temperature and RH

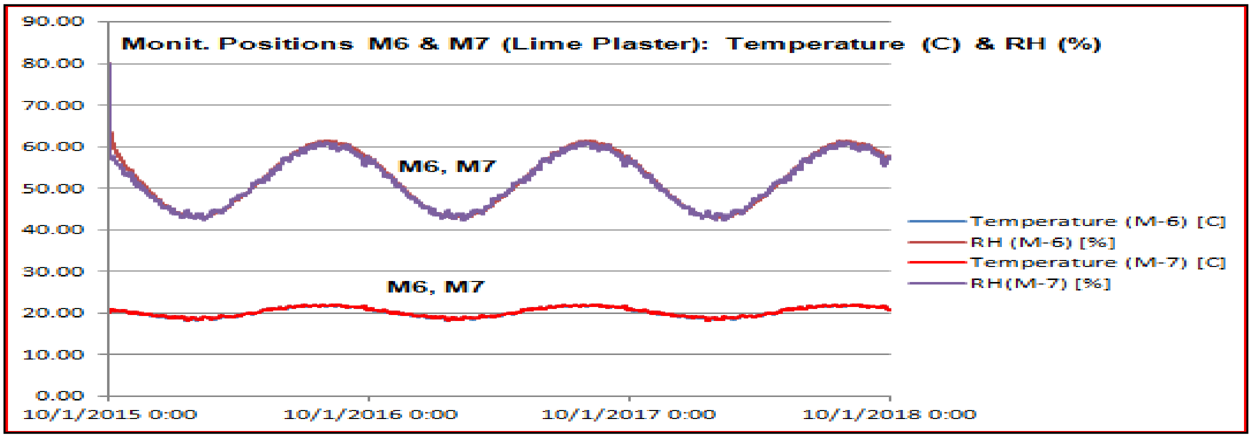


Figure 38: Lime Plaster- Middle (M6) & Interior Surface (M7): Temperature and RH

RH (Figure 36-38) too has initially decreased and thereafter established a regular pattern of seasonal fluctuation at each of the monitoring position. In the assembly, there is no favorable situation for mold growth [According to Viitanen et al (2010), the minimum (critical) ambient humidity has to be between RH 80 - 95 % for mould growth and for decay, above 95% RH]. In addition, because of excellent moisture buffering features of hempcrete, mold growth in hempcrete wall will be very unlikely. Further to confirm the status of mold growth in internal surface, mold isopleths distribution was analyzed.

Table below (Table 17) summarizes the range of temperature and RH at monitoring positions during simulation period.

Lime Render			
Monit. Position 1		Monit. Position 2	
Temp[C]	RH[%]	Temp[C]	RH[%]
(-) 23.83-39.82	16.09-100.00	[-] 23.53-39.24	42.98-99.85

Hempcrete					
Monit. Position 3		Monit. Position 4		Monit. Position 5	
Temp[C]	RH[%]	Temp[C]	RH[%]	Temp[C]	RH[%]
[-] 22.94-38.30	60.31-99.26	[-] 1.35-24.97	76.04-81.01	17.73-22.25	42.55-80.00

Lime Plaster			
Monit. Position 6		Monit. Position 7	
Temp[C]	RH[%]	Temp[C]	RH[%]
18.06-22.21	42.61-80.00	18.18-22.19	42.38-80.00

Table 17: Range of Temperature and RH at monitoring positions

7.6.1.2.2 Mold Isopleths Distribution

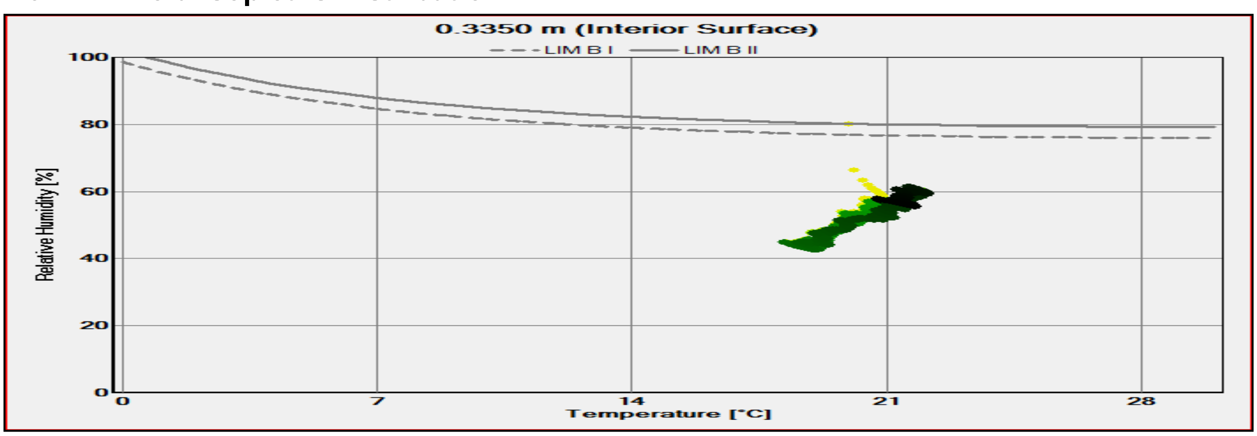


Figure 39: Isopleths at Internal surface (Monitoring Position 7)

As it can be confirmed from figure above (Figure 39), mold Isopleths [time steps (1hour) or scattered graph of RH and temperature] at internal surface lies well below the dotted curve (for hygroscopic material) and manifests no risk of mold growth at all.

7.6.1.3 Freeze thaw and Subflorescence (salt) Risks

Since there is no long time accumulation of moisture in the assembly, no damage from freeze thaw and salt effect (clogging the pore and limiting the permeability of materials) can be expected.

7.6.1.4 Profiles

Profile represents the status of RH, temperature and WC at starting and end of the simulation period at cross section of the wall (Figure 40).

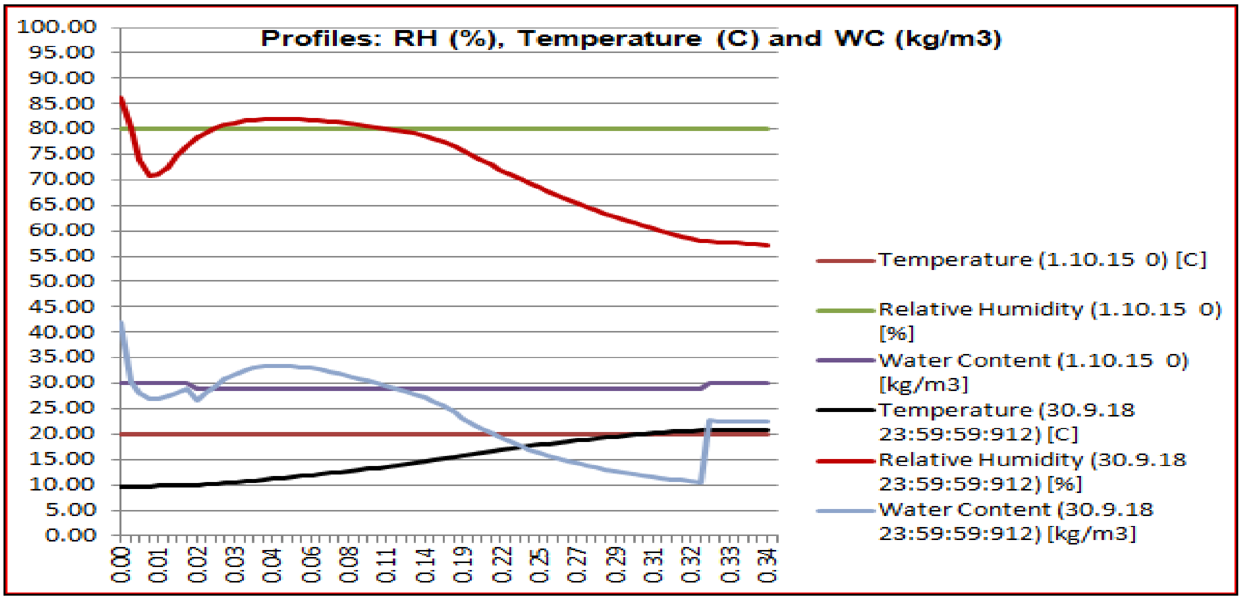


Figure 40: Temperature, RH and WC profiles at starting and end of simulation period

In the end of simulation scenario (Figure 40), both RH and WC around exterior surface of hempcrete were high, but later it was decreased as time progressed.

Table 18 below shows range of the temperature, RH and WC at the starting and end of simulation period of whole wall section.

Description	At 1.10.15 0	At 30.9.18 23:59:59:912
Temperature	20C	9.60-20.86C
RH	80.00%	57.21-86.04%
WC	29-30kg/m3	10.56-42.08kg/m3

Table 18: Ranges of Temperature, RH and WC at starting and end of simulation period

7.6.2 Wall Assembly 2

7.6.2.1 Condensation Risks

7.6.2.1.1 Total Water Content

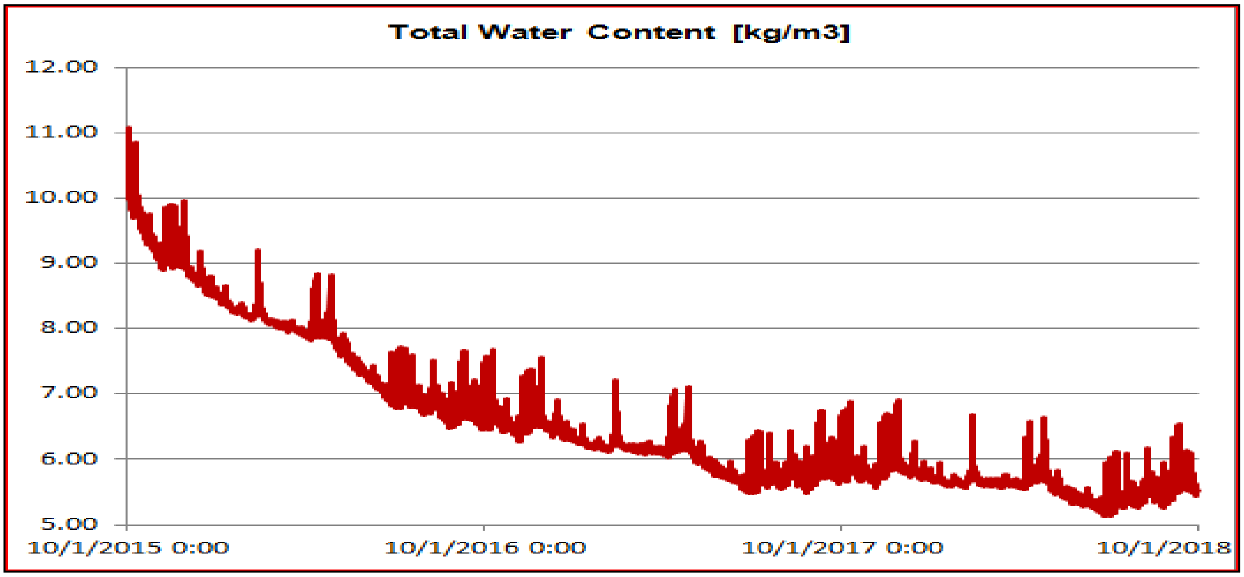


Figure 41: Total Water Content

Regular pattern of seasonal fluctuation and decrement in WC over time has shown by Total WC (Figure 41). No long time accumulation of water at one point is observed and present value of total WC (in the range of 0.18-0.39%mass) is much lower (about -26%) than assembly 1. Moreover, the assembly is drying out faster than assembly 1 and is expected to reach in dynamic steady state earlier under the applied climatic conditions.

7.6.2.1.2 Water Content in Individual Layer

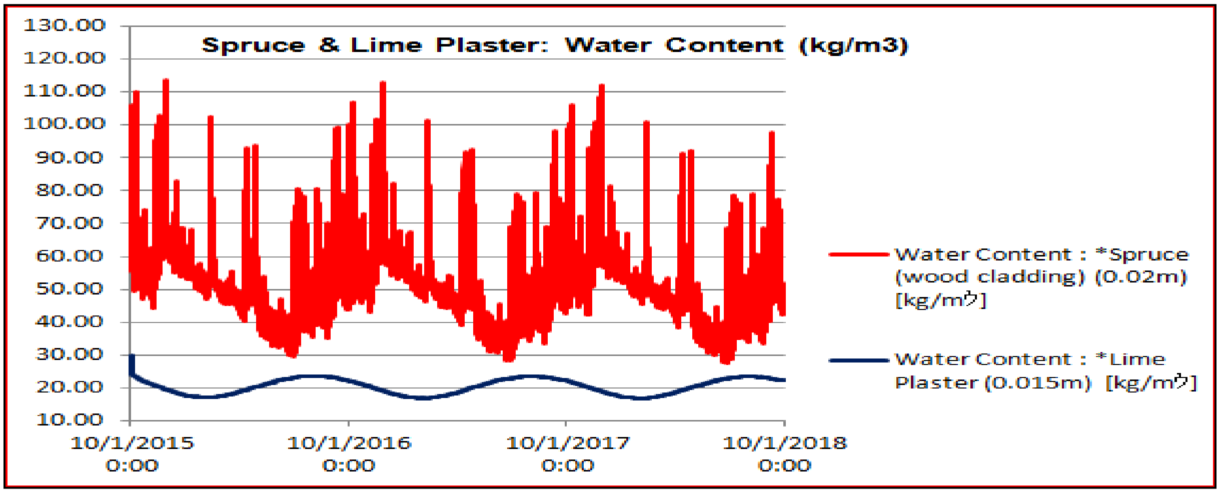


Figure 42: WC in Spruce and Lime Plaster

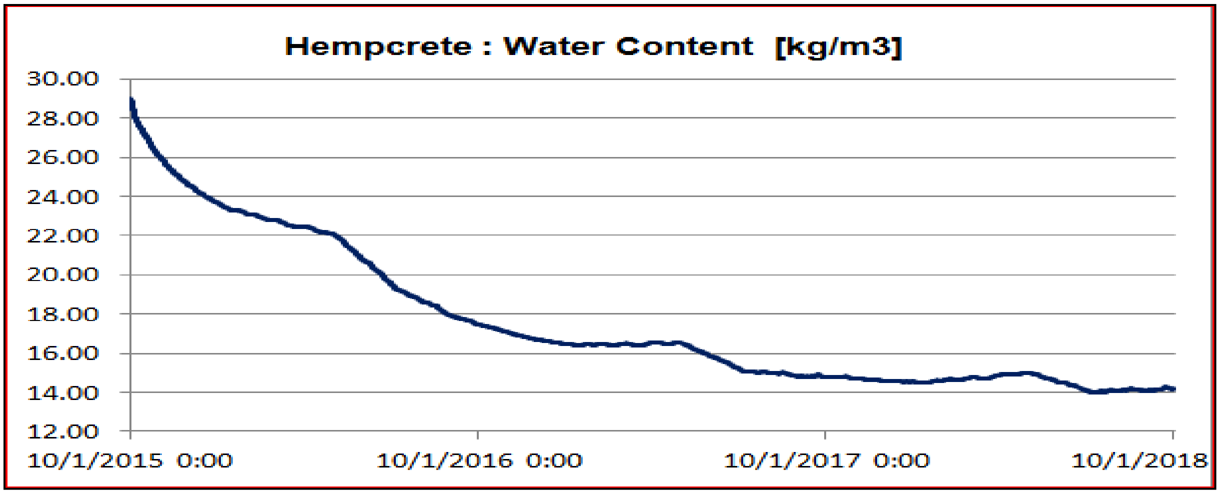


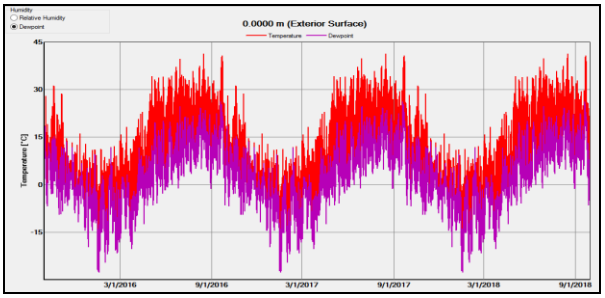
Figure 43: WC in Hempcrete

As shown in Figure 42, WC in lime plaster has reached to dynamic equilibrium from the early cycles. However, WC in hempcrete and spruce (Figures 42-43) are diminishing continuously, which indicates it is drying out fast and will reach in equilibrium earlier. WC in hempcrete is significantly decreased (by about 52%) from assembly 1.So far no moisture accumulation has noticed occurred for long time in any individual layer, WC in each layer is less than 10%mass (except in exterior surface of spruce).Therefore, any risk of condensation, rot or mould growth, heat loss, subflorescence (salt effect) and freeze thaw damage from WC aspects in hempcrete is unlikely. Below table (Table 19) highlights the range of total and individual layer WC during simulation period.

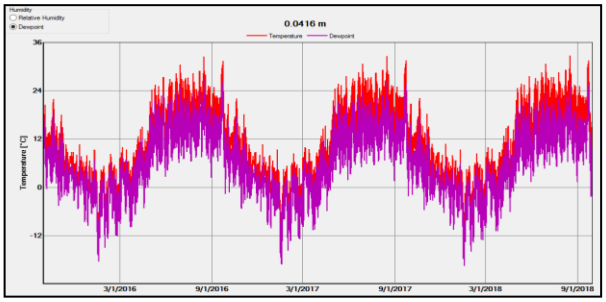
Water Content (kg/m3) (%Mass)				
Spruce	**Air Layer**	**Hempcrete**	**Lime Plaster**	**Total**
27.55-113.64 (6.89-28.41%M)	0.01-0,02 (0.76-1.17%M)	13.98-29.00 (3.60-7.47%M)	16.76-30.00 (1.05-1.88%M)	5.13-11.08 (0.18-0.39%M)

Table 19: Range of WC in assembly

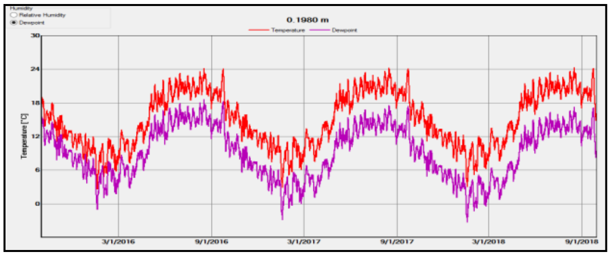
7.6.2.1.3 Dew Points



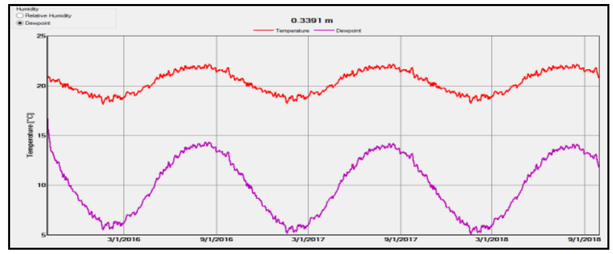
Spruce- Exterior Surface (M-1)



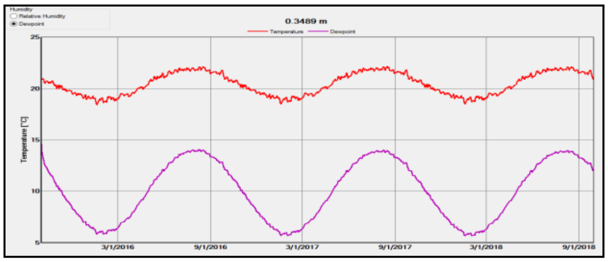
Hempcrete Exterior (M-2)



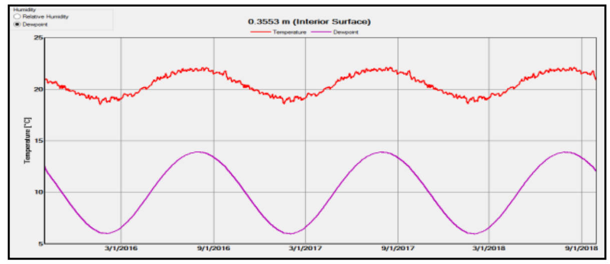
Hempcrete- Middle (M-3)



Interior (M-4)



Lime Plaster- Middle (M-5)



Interior Surface (M-6)

Figure 44: Dew Points at Monitoring Positions

As shown in Figure 44, up to the exterior surface of hempcrete (positions 1-2), dew point is very close to temperature, but WC profiles confirm that there is no evidence of water accumulation and condensation. At the monitoring positions 3-6 (interior surface) dew point falls well below the temperature. Therefore from both the factors (dew point and WC), no condensation risk is seen in the entire assembly.

7.6.2.2 Mold Risk

7.6.2.2.1 Temperature and RH

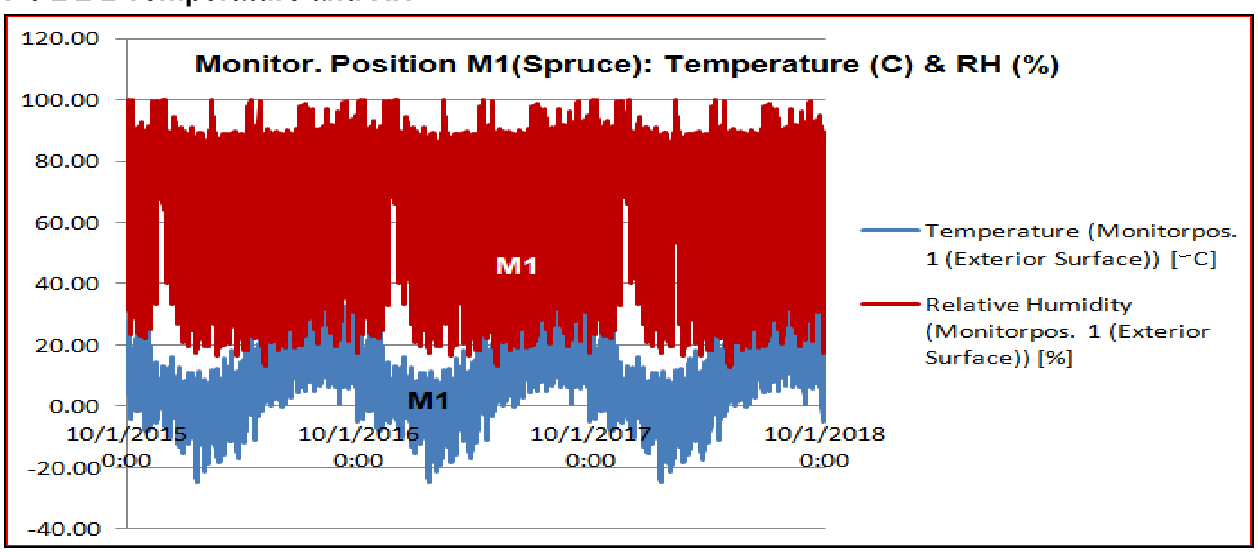


Figure 45: Spruce- Exterior Surface (M1): Temperature and RH

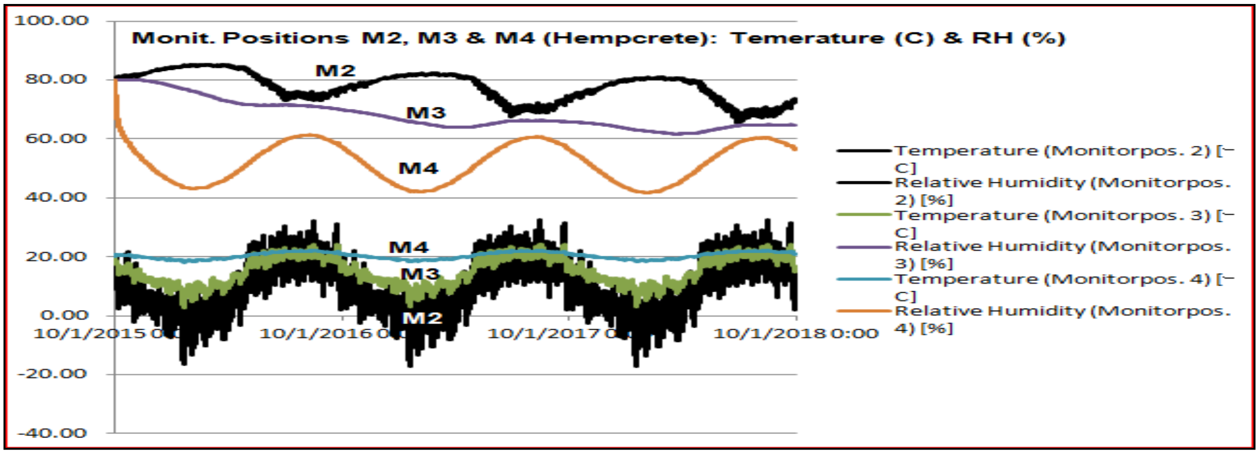


Figure 46: Hempcrete- Exterior (M2), Middle (M3) & Interior (M4): Temperature and RH

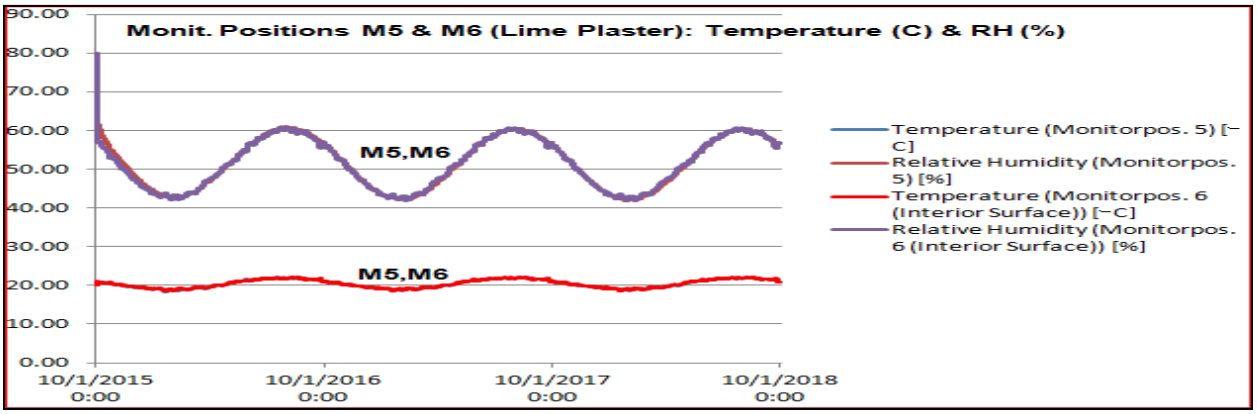


Figure 47: Lime Plaster- Middle (M5) & Interior Surface (M6): Temperature and RH

No favorable situation (high RH and high temperature) to mold growth is evidenced (Figure 45-47) in the assembly. However, to confirm the status of mold growth, mold isopleths distribution was further assessed. Table below (Table 20) summarizes the range of temperature and RH at monitoring positions during simulation period.

Spruce	
Monit. Position 1	
Temp[C]	**RH[%]**
(-) 24.74-41.30	12.88-99.94

Hempcrete					
Monit. Position 2		**Monit. Position 3**		**Monit. Position 4**	
Temp[C]	**RH[%]**	**Temp[C]**	**RH[%]**	**Temp[C]**	**RH[%]**
[-] 17.21-32.65	65.52-85.32	2.62-24.28	61.57-80.11	18.13-22.18	41.68-80.00

Lime Plaster			
Monit. Position 5		**Monit. Position 6**	
Temp[C]	**RH[%]**	**Temp[C]**	**RH[%]**
18.41-22.15	41.92-80.00	18.51-22.14	41.94-80.00

Table 20: Range of Temperature and RH at monitoring positions

7.6.2.2.2 Mold Isopleths Distribution

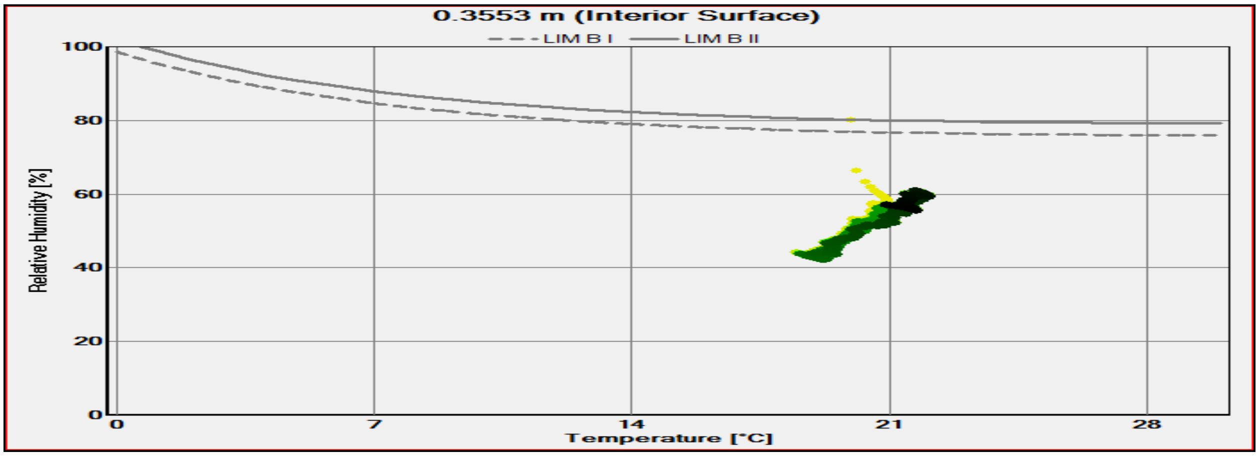


Figure 48: Isopleths at Internal surface (Monitoring Position 6)

As it can be confirmed from figure above (Figure 48), mold Isopleths at internal surface lies well below the dotted curve (for hygroscopic material) and manifests no risk of mold growth at all.

7.6.2.3 Freeze thaw and Subflorescence (salt) Risks

As in the base case, since there is no long time accumulation of moisture in the assembly, no damage from freeze thaw and salt effect (clogging of pores) can be expected.

7.6.2.4 Profiles

Profile represents the status of RH, temperature and WC at starting and end of the simulation period at cross section of the wall (Figure 49).

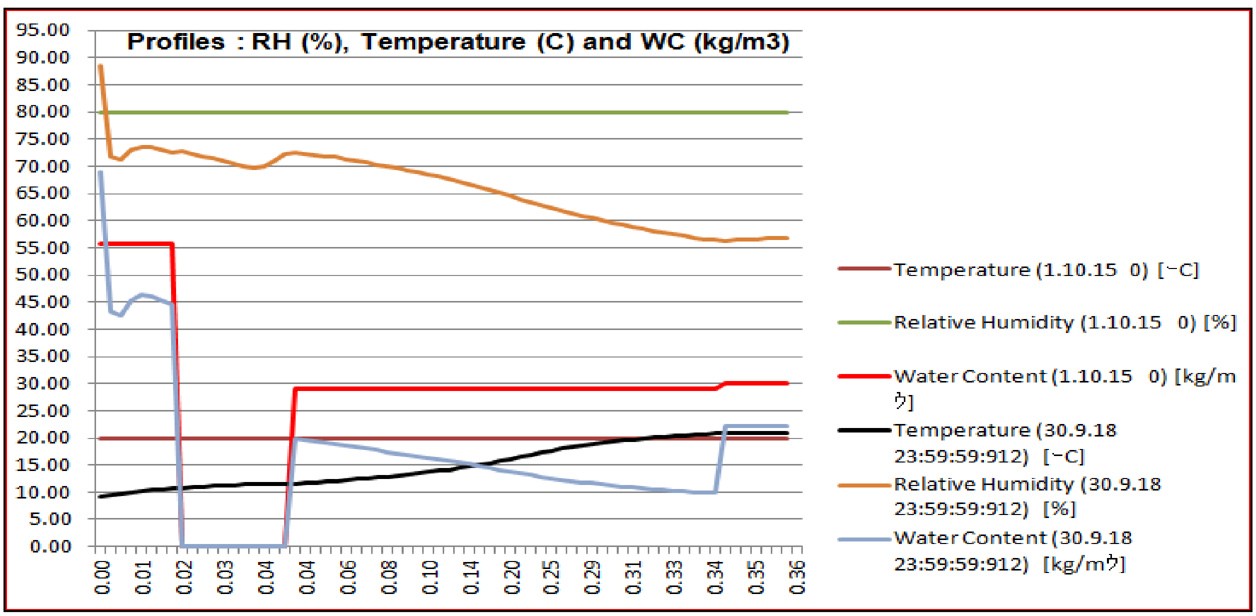


Figure 49: Temperature, RH and WC profile at starting and end of simulation period

As shown in the end of the simulation scenario (Figure 49), RH and WC in hempcrete were very low and also were decreasing since the starting of simulation.

Table 21 below shows the ranges of temperature, RH and WC at the starting and end of simulation period of whole wall section.

Description	At 1.10.15 0	At 30.9.18 23:59:59:912
Temperature	20C	9.22-20.96C
RH	80.00%	56.36-88.60%
WC	0-55.83kg/m3	0-68.93kg/m3

Table 21: Ranges of Temperature, RH and WC at starting and end of simulation period

7.6.3 Sensitivity Analysis

To comprehend the degree of changes in hygrothermal parameters of hempcrete (base) wall, series (four) of sensitivity analysis for under mentioned references (for hempcrete) were conducted for wall assembly 1.

1. **Sensitivity Analysis 1**: Using reference moisture sorption values: Porosity= 0.73 m3/m3, $WC_{80\%EQUIV}$=33kg/m3, W_{max}= 730kg/m3 and W_f =546kg/m3; to understand the impact of WC in the performance of hempcrete wall.
2. **Sensitivity Analysis 2**: Using reference dry “k” value= 0.115W/mK (high) and moist “k” value= 0.768 W/mK (avoiding thermal conductivity supplement b) to understand the impact of high “k” value (low thermal insulation)
3. **Sensitivity Analysis 3**: Using intermediate reference dry “k” value= 0.09W/mK to understand the influence of intermediary thermal insulation
4. **Sensitivity Analysis 4**: Using low reference dry “k” value= 0.06W/mK to understand the hygrothermal behavior of wall in high thermal insulation scenario.

No change is made in boundary conditions, climate file, orientation and assumptions from base case. Followings are the findings of sensitivity analysis:

7.6.3.1 Sensitivity Analysis 1

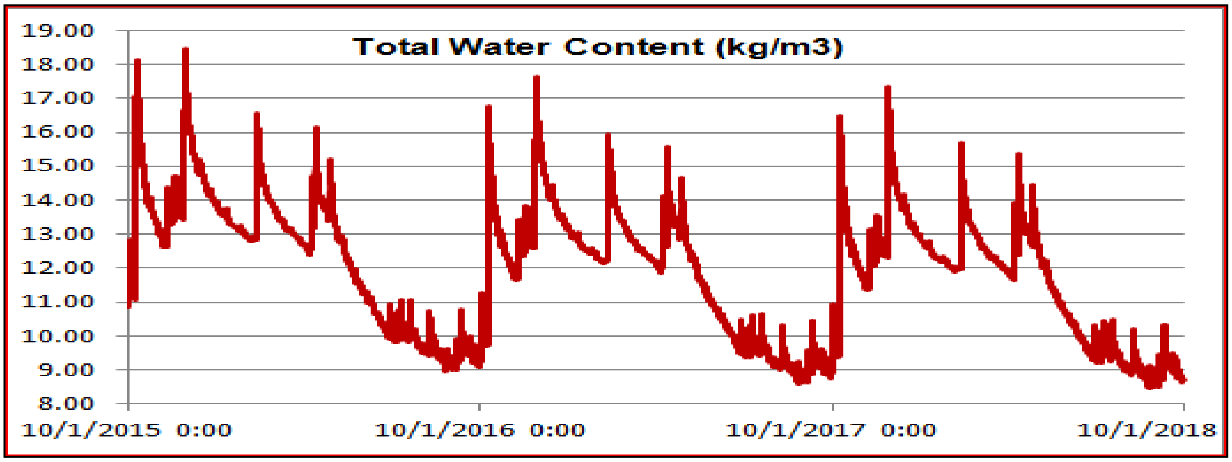


Figure 50: Total Water Content (Sensitivity Analysis 1)

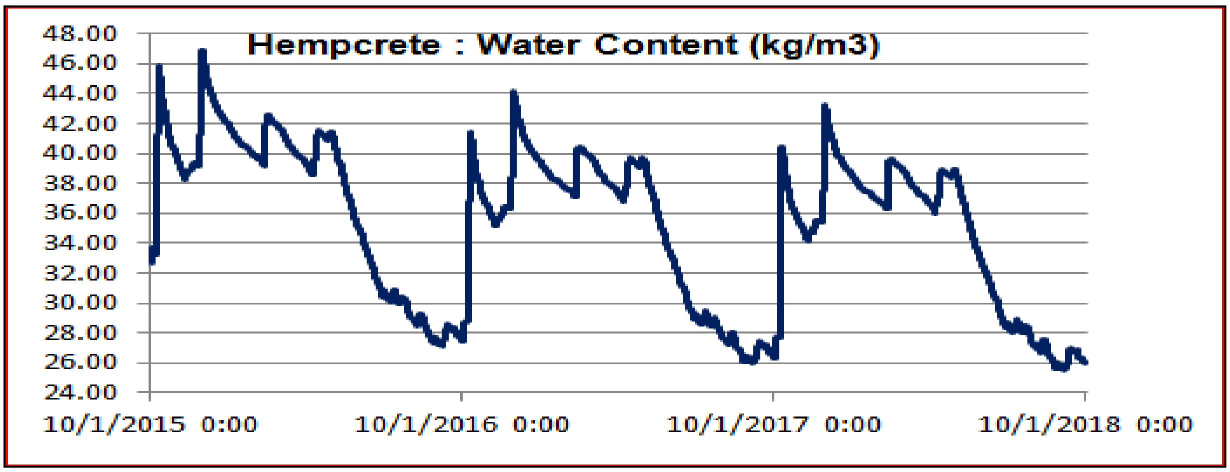


Figure 51: Water Content in Hempcrete (Sensitivity Analysis 1)

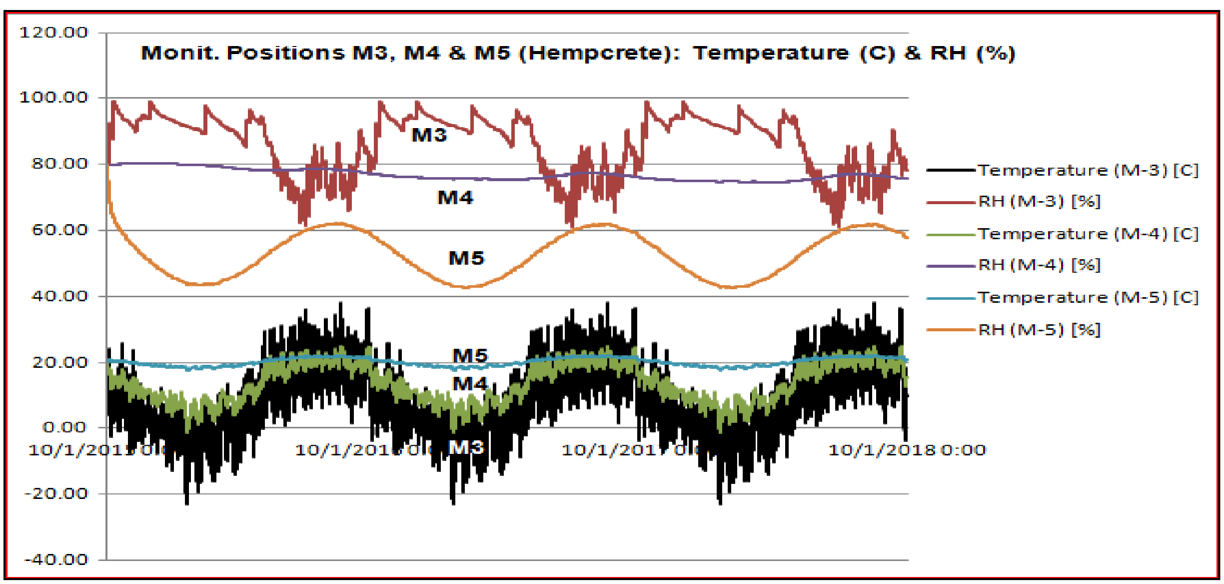


Figure 52: Hempcrete-Temperature and RH (Sensitivity Analysis 1)

7.6.3.2 Sensitivity Analysis 2

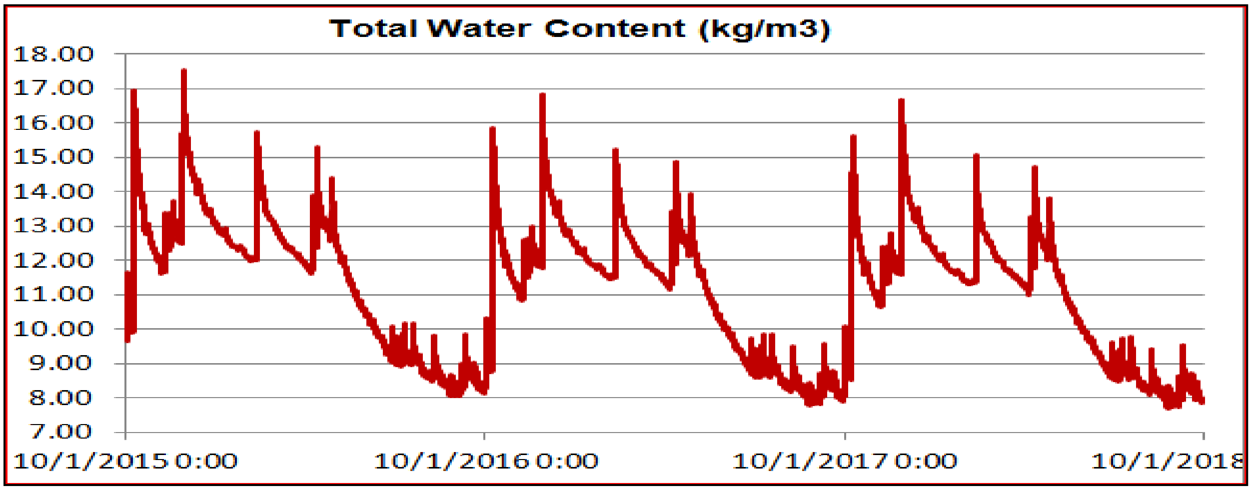


Figure 53: Total Water Content (Sensitivity Analysis 2)

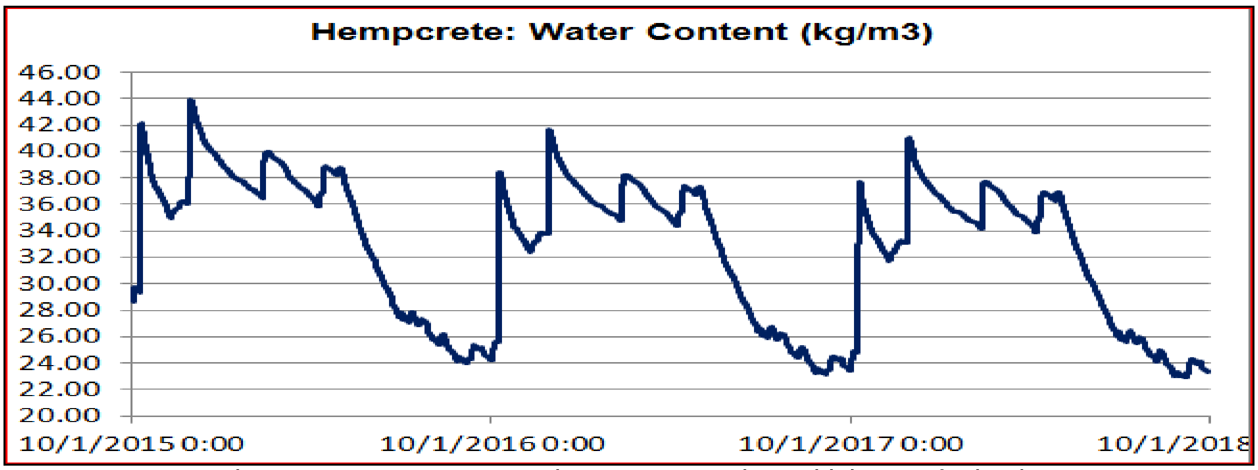


Figure 54: Water Content in Hempcrete (Sensitivity Analysis 2)

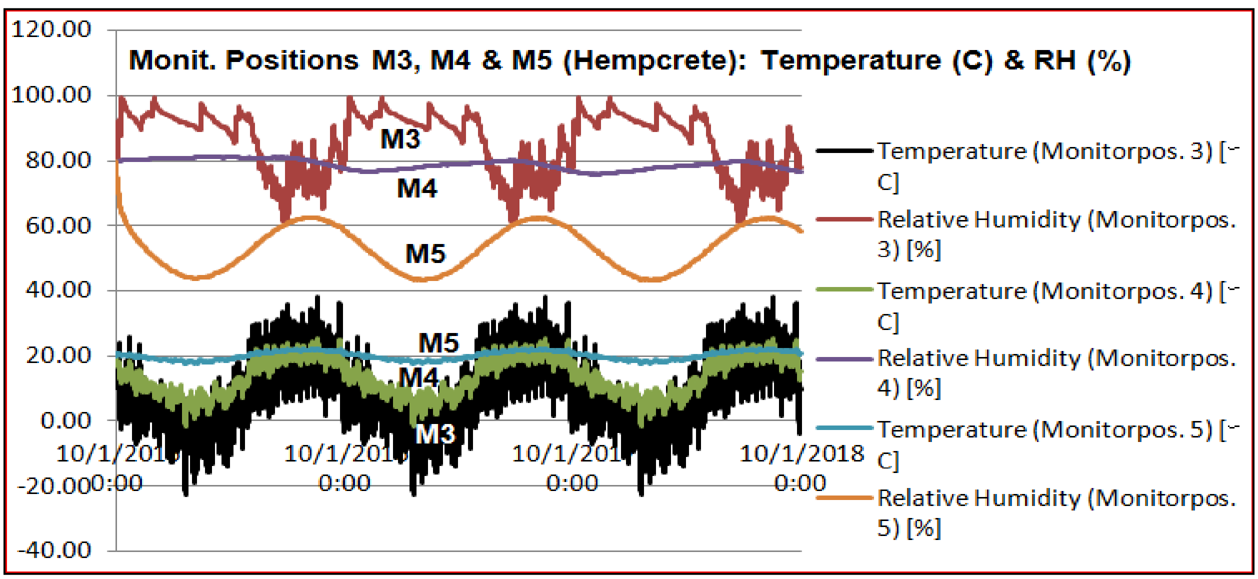


Figure 55: Hempcrete-Temperature and RH (Sensitivity Analysis 2)

7.6.3.3 Sensitivity Analysis 3

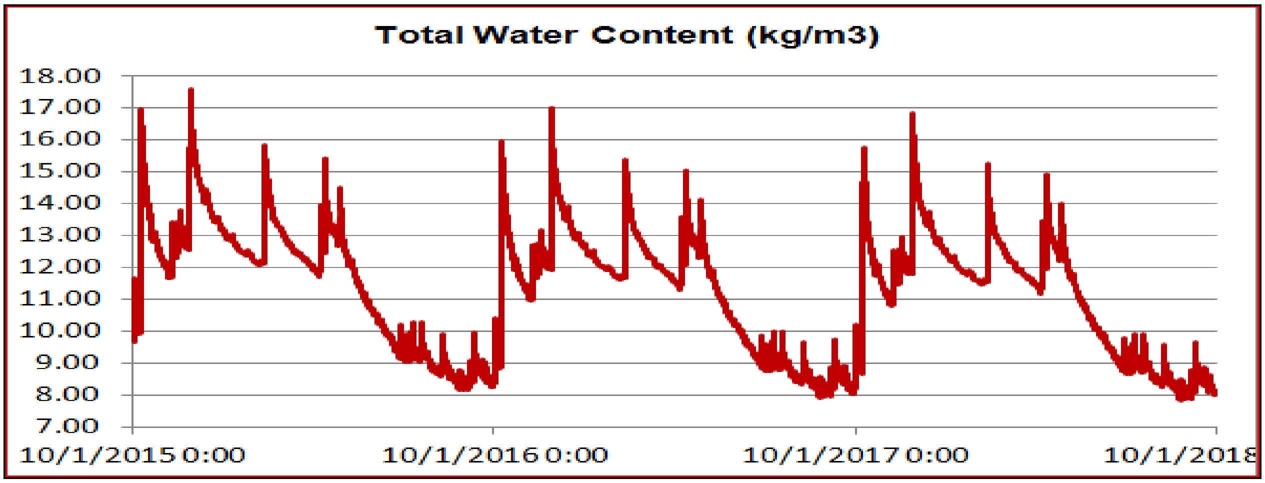


Figure 56: Total Water Content (Sensitivity Analysis 3)

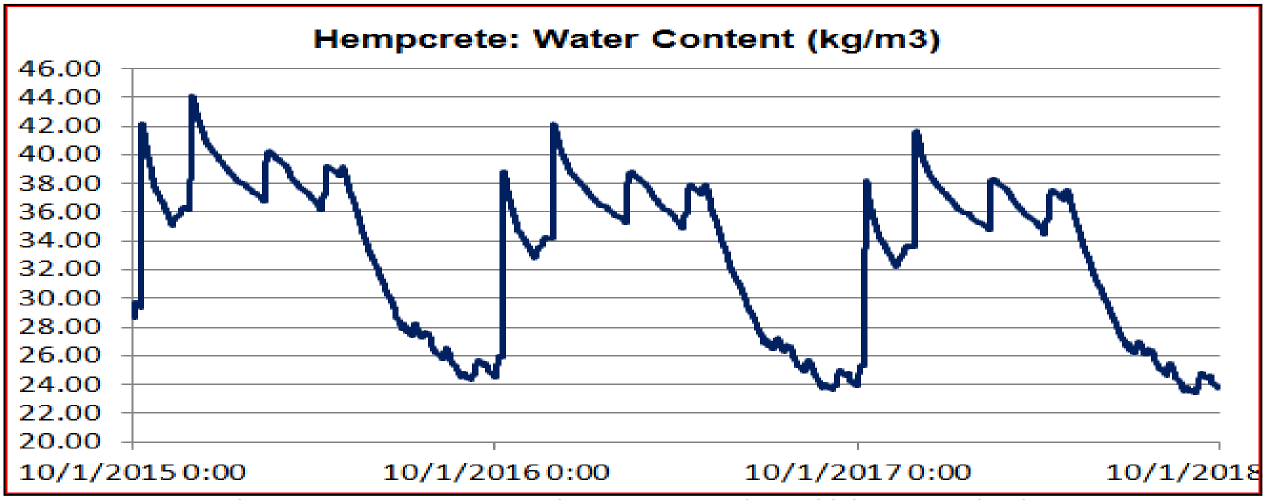


Figure 57: Water Content in Hempcrete (Sensitivity Analysis 3)

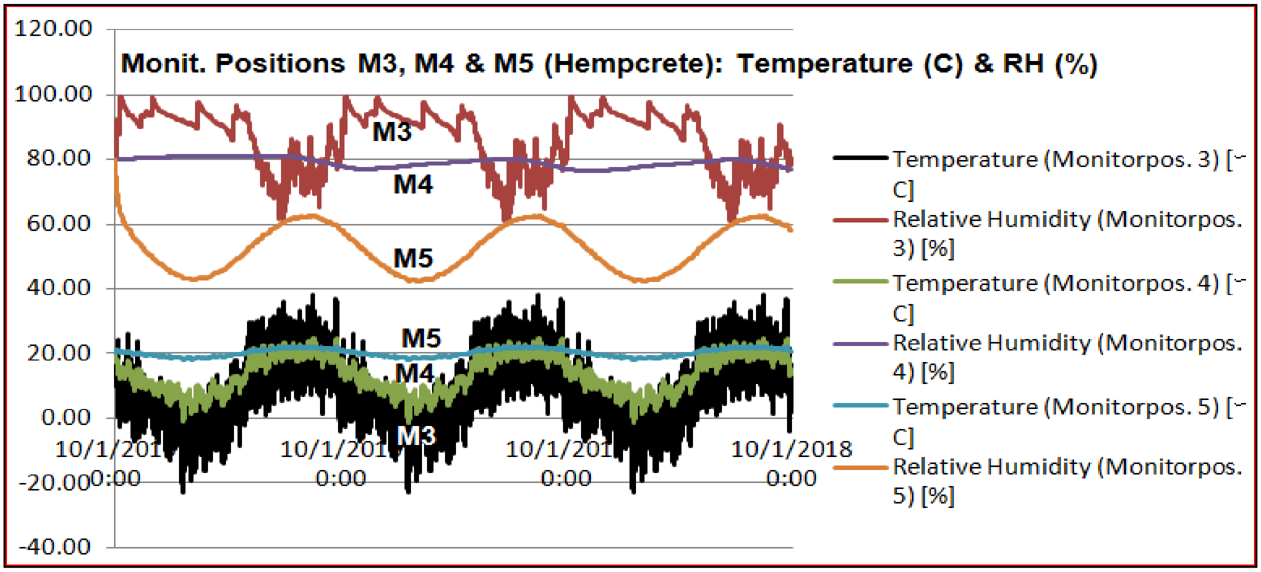


Figure 58: Hempcrete-Temperature and RH (Sensitivity Analysis 3)

7.6.3.4 Sensitivity Analysis 4

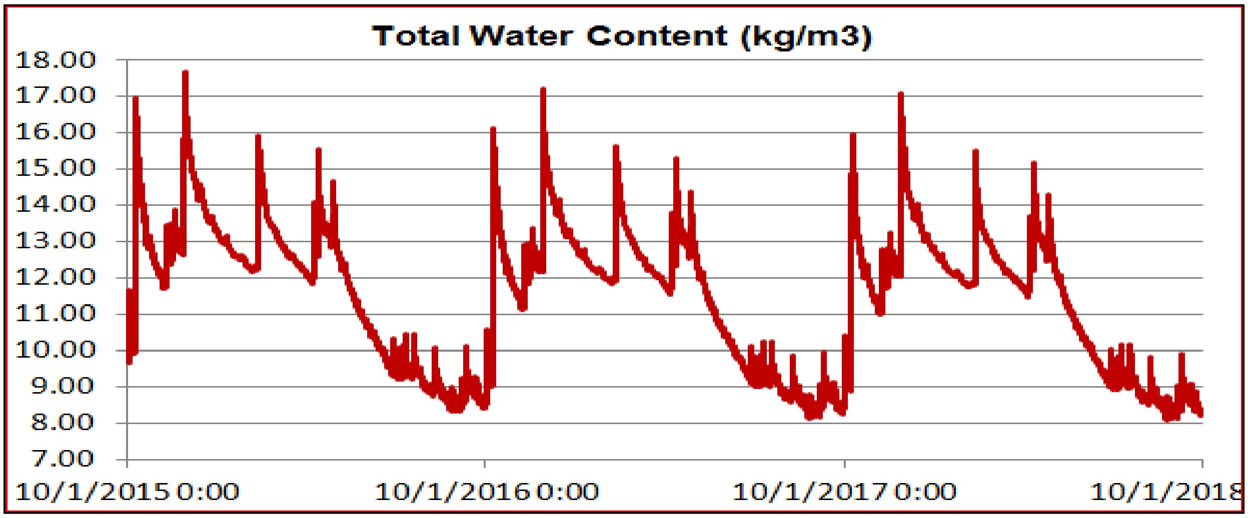


Figure 59: Total Water Content (Sensitivity Analysis 4)

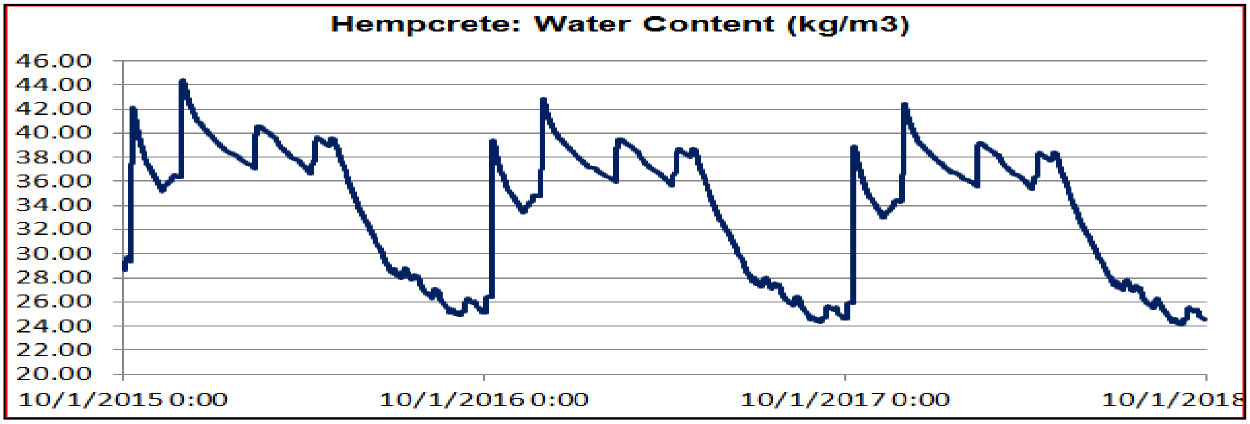


Figure 60: Water Content in Hempcrete (Sensitivity Analysis 4)

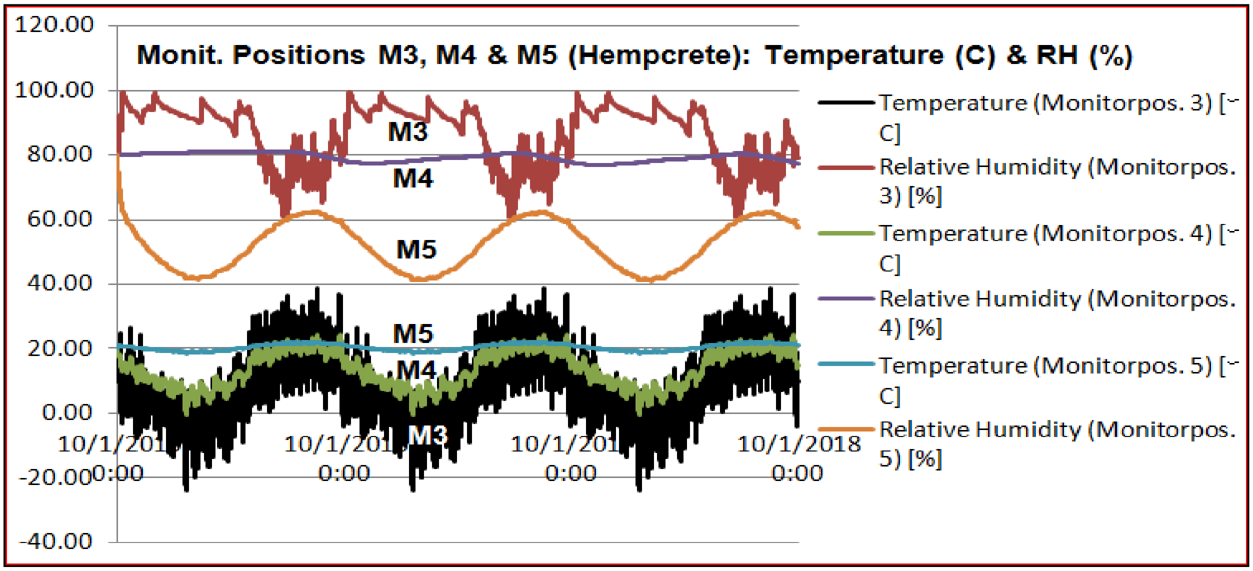


Figure 61: Hempcrete-Temperature and RH (Sensitivity Analysis 4)

Table below (Table 22) highlights the range of WC in assembly in sensitivity analysis during simulation period

Sensitivity Analysis	Water Content (kg/m3) (%Mass)			
	Lime Render	Hempcrete	Lime Plaster	Total
1	18.07-229.21 (1.13-14.33%M)	25.54- 46.93 (6.58-12.09%M)	17.05-30.00 (1.07-1.88%M)	8.47-18.47 (0.24-0.51%M)
2	17.96-228.70 (1.12-14.29%M)	22.90-43.95 (5.62-11.28%M)	17.20-30.00 (1.07-1.88%M)	7.70-17.53 (0.21-0.49%M)
3	17.94-228.74 (1.12-14.29%M)	23.38-44.15 (6.02-11.38%M)	16.95-30.00 (1.06-1.88%M)	7.84-17.59 (0,22-0.49%M)
4	17.90-228.79 (1.12-14.30)	24.16-44.41 (6.23-11.45%M)	16.62-30.00 (1.04-1.88%M)	8.08-17.67 (0.23-0.49%M)

Table 22: Range of WC in Sensitivity Analysis

Similar to base case, in sensitivity analysis too total and individual layer WC has shown (Figure 50- 61) a regular pattern of seasonal fluctuation and are in almost similar range to base case (Table 22); WC is below 15% in each layer throughout the simulation period. The wall is drying out fast and is approaching to dynamic equilibrium. No long time accumulation of water at one point in any layer has been observed. Alike base case, up to the middle of hempcrete (monitoring positions 1-4) dew point is very close to temperature. RH and temperature profiles (Figure 50-61) are mimicking the base case and no significant changes are observed from the base case. As in the base case, mold isopleths at internal surface (in all sensitivity cases) too is well below the dotted curve. Therefore, in overall, the degree of change (on WC, RH, temperature, dew point, isopleths etc.) in sensitivity analysis is negligible. (See Appendix D for end of the simulation profiles, isopleths, film and lime render and plaster WC, RH and temperature).

7.6.4 Discussion on WUFI Modelling

The outcomes of Assembly 1 base case and sensitivity analysis are pretty similar (RH, temperature, dew point, Isopleths, heat flux, heat transmission, film and end of simulation profile); only a small change (increment) in WC (about 6.5%) in hempcrete is noticed in sensitivity analysis 1 because of high moisture sorption inputs. In all cases no any hygrothermal issues such as condensation, rot or mould growth, reducing efficiency of insulation, subflorescence (salt effect) and freeze thaw damage have been perceived and the assembly is performing very well. Hence, it can be concluded that there will be no significant changes in hygrothermal characteristic of hempcrete wall due to some variations in moisture sorption and thermal conductivity.

While comparing assembly 2 (rain screen) with assembly 1 in the same circumstances, it is noticed that former is performing much better in each of the hygrothermal parameters. The assembly is drying out fast (expected to reach in dynamic steady state much earlier than assembly 1), current WC range is very low compare to assembly 1 (-34% and -25% in hempcrete and total WC respectively) and there is no risk of condensation, frost and salt damage, heat loss and mold growth in the assembly. Therefore, wall assembly 2 (rain screen system) would be the best option for hempcrete in the climate of Toronto and can be considered as ideal from hygrothermal point of view.

For detail information on WUFI literature and analysis, refer Appendix B and Appendix D.

8.0 Conclusions

In this study, an in depth literature review was conducted to understand the hygrothermal parameters of hempcrete and to acquire best appropriate reference values of its properties to utilize in WUFI modelling. Then, laboratory testing was done for 3 different mixes of hempcrete (hemp to binder ratio-1:1, 1:1.5 and 1:2) to measure dry density, porosity, free water saturation, maximum water content and saturation coefficient. The reason behind testing 3 different mixes was to understand the influence of binder in hempcrete properties. Values measured from the tests were:

- Dry density (oven dry): 233kg/m3, 317kg/m3 and 388kg/m3 (almost in linear mode with proportion to binder)
- W_f (48 hours cold water submersion): 376kg/m3, 375kg/m3 and 424kg/m3
- W_{max} (5 hour boiling): 533kg/m3, 526kg/m3 and 655kg/m3,
- Porosity (W_{max}/ ρ_{water}): 0.52m3/m3, 0.52m3/m3 and 0.66 m3/m3 and
- Saturation Coefficient (W_f / W_{max}): 0.71, 0.71 and 0.65
  for mix1, mix 2 and mix 3 respectively.

Tests were conducted in accordance with ASTM C67-14 and ASTM C62-13a standards. Among the test results, dry densities were in good agreement with reference values; however, water related parameters were not in fully satisfactory ranges compared to references because of applications of static tests.

Further, based on the most reliable reference R values (R2-2.5/inch), minimum wall thickness required to meet OBC (compliance package- building using space heating equipment with AFUE ≥ 90%, Zone 1) was assessed and concluded that wall thickness of 300mm will be ideal to meet OBC requirements (R22-R27).

In addition, to establish hygrotermal performance of hempcrete in the Canadian context, one-dimensional transient hygrothermal analysis for 300mm thick, mix 3 wall (to balance both the structural integrity and insulation) was conducted in WUFI Pro 5.3 software. Since WUFI doesn't contain material database for hempcrete, a new database was introduced for hempcrete by using both lab tested values and best appropriate reference values. Simulations (followed by series of sensitivity analysis) were carried out for below mentioned two types of wall assemblies; with and without sun, rain and wind exposure.

1. Assembly 1: Lime render (20mm) + Hempcrete (300mm) + Lime plaster (15mm); Total thickness: 335mm
2. Assembly 2: Wood cladding (spruce) (20mm) + Air layer-vented (20mm) + Typar + Hempcrete (300mm) + Lime plaster (15mm); Total thickness: 355 mm (rain screen system)

WUFI analysis showed both the assemblies were performing well in all the hygrothermal parameters without any issue. However, in comparison to assembly 1, assembly 2 was performing much better (low WC, drying fast and reaching to dynamic steady state earlier). Therefore, Assembly 2 (rain screen) could be considered as best option for hempcrete wall assembly in the context of Canada. Furthermore, no significant impacts on hygrothermal characteristic of hempcrete wall were noticed during sensitivity analysis due to some variations in moisture sorption and thermal conductivity (dry and moist state).

As a concluding remark, although this research has many limitations and uncertainties, still it is expected that this work may help the architects and designers to optimize effective performances and comfort feeling in their buildings and to save global energy with the use of hempcrete.

Further research on hygrothermal performance of hempcrete wall (using Canada grown hemp) is recommended to carry out by measuring thermal conductivity in various mean temperatures.

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Appendices

Appendix A: Life Cycle Analysis (LCA), Embodied Carbon and OBC Supplementary Standard SB-12

This section presents the LCA and Embodied Carbon of hempcrete.

1. Life Cycle Analysis (LCA)

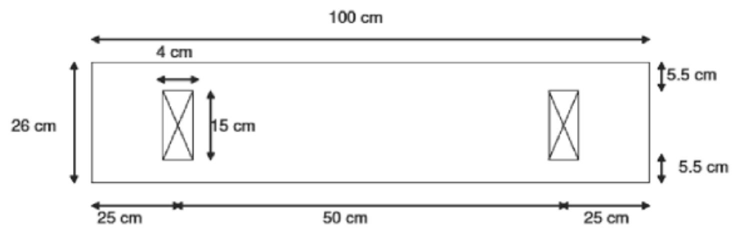


Figure 1: Transversal cross-section of the functional unit (Arnaud & Amziane, 2013)

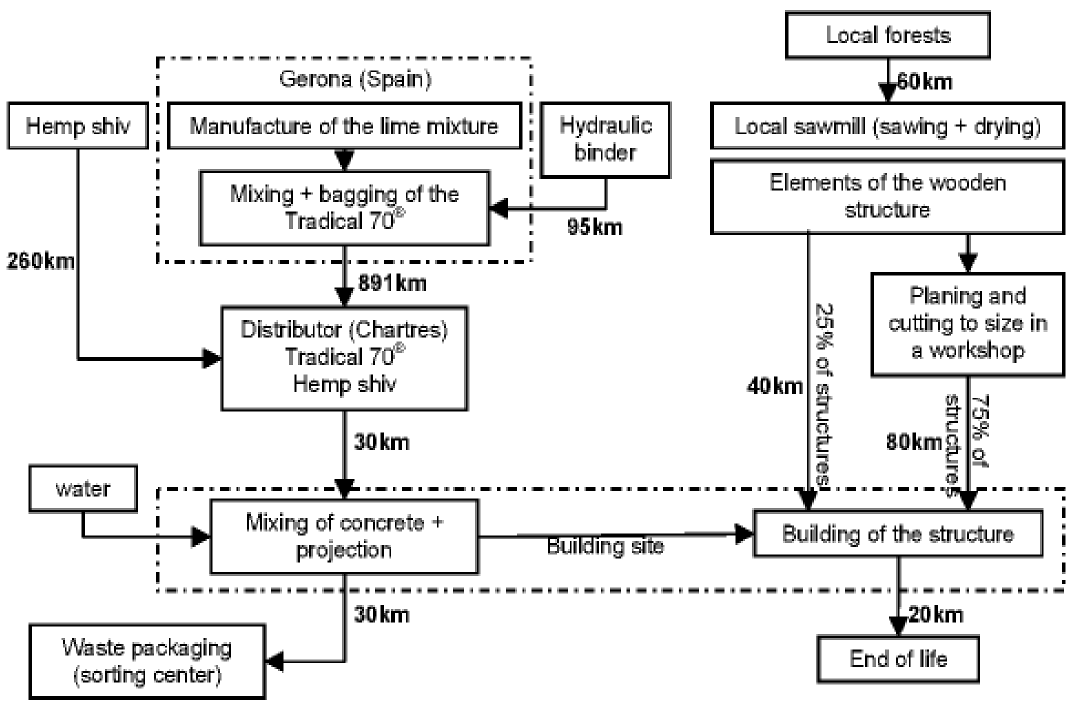


Figure 2: Reference scinario of LCA BCB-Lhoist, (Arnaud & Amziane, 2013)

Impacts	Production of primary materials			Installation	Operation al lifetime	End of life	Transport (total)	Total	
	Hemp shiv		Other prim. mat.					Mass	Economic
	Mass	Economic							
Resource exhaustion (kg Sb eq.)	2.9×10^{2}	1.5×10^{2}	7.7×10^{2}	1.2×10^{3}	0	0	2.6×10^{2}	1.3×10^{1}	1.2×10^{1}
Atmospheric acidification (kg SO_2 eq.)	5.1×10^{4}	2.7×10^{2}	4.8×10^{4}	1.3×10^{3}	0	0	5.1×10^{3}	1.0×10^{4}	8.2×10^{4}
Greenhouse effect (100yrs) *including carbon storage* (kg CO_2 eq.)	-45.9 *Shiv* =-52.2	-24.5 *Shiv* =-27.9	23.1 *Wood* =-9.9	0.2 *0*	-13.6 *Lime* =-13.6	0 *0*	6.7×10^{4} *0*	-35.5 -73.7	-14.1 -51.4
Destruction of the ozone layer (kg CFC-11 eq.)	7.1×10^{7}	3.8×10^{7}	3.3×10^{4}	3.4×10^{7}	0	0	5.7×10^{4}	9.9×10^{4}	9.7×10^{4}
Formation of photochemical ozone (kg C_2H_4 eq.)	7.1×10^{4}	3.8×10^{4}	4.2×10^{3}	5.0×10^{3}	0	0	3.8×10^{4}	5.4×10^{3}	5.0×10^{3}
Non-renewable energy (MJ)	52.3	27.9	265.8	19.9	0	0	56.3	394.2	369.9
Air pollution (m^3)	674	360	207.2	14.6	0	0	128.2	1024	709.9
Water pollution (m^3)	4.3	2.3	2.2	6.1×10^{4}	0	0	1.1×10^{4}	6.7	4.7
Waste production (kg)	6	3.2	No data	0.9	0	98	No data	104.9	102.1

Table 1: Possible environmental effects over 100 years

(Arnaud & Amziane, 2013)

For functional unit, all the results to be divided by 100 (a typical lifetime).

2. Embodied Carbon

	Embodied Carbon (kgCO_2 m^2)	Assumptions	Sources
Hempcrete	-2.7	Range -6.38 - +3.50	
Transport	0.5	100 km	
Installation (mixing and drying)	0.92	from cottage installation	Miskin (2010)
Maintenance	0.8	20% replacement over 60 years	
End of Life	0.4	Crush and reuse	
Total	**-0.08**	3	4

Table1: Embodied Carbon of hempcrete per m2 at 100mm thickness taking account of installation, maintenance and end of life disposal

(Wright et al, 2012)

The above (Table 1) embodied carbon of hempcrete represents a “most likely” current scenario, where the hemp is grown in monoculture using typical wood farming and the lime is sourced from a centralized facility (Miskin, as cited in Wright et al, 2012).

3. OBC Supplementary Standard SB-12

Table 2.1.1.2.A
ZONE 1 - Compliance Packages for Space Heating Equipment with AFUE ≥90%
Forming Part of Sentence 2.1.1.2.(1)

Component	Compliance Package												
	A	B	C	D	E	F	G	H	I	J	K[3]	L[4]	M[5]
Ceiling with Attic Space Minimum RSI (R)-Value[1]	8.81 (R50)	8.81 (R50)	8.81 (R50)	8.81 (R50)	8.81 (R50)	8.81 (R50)	8.81 (R50)	8.81 (R50)	8.81 (R50)	8.81 (R50)	8.81 (R50)	8.81 (R50)	8.81 (R50)
Ceiling Without Attic Space Minimum RSI (R)-Value[1]	5.46 (R31)	5.46 (R31)	5.46 (R31)	5.46 (R31)	5.46 (R31)	5.46 (R31)	5.46 (R31)	5.46 (R31)	5.46 (R31)	5.46 (R31)	5.46 (R31)	5.46 (R31)	5.46 (R31)
Exposed Floor Minimum RSI (R)-Value[1]	5.46 (R31)	5.46 (R31)	5.46 (R31)	5.46 (R31)	5.46 (R31)	5.46 (R31)	5.46 (R31)	5.46 (R31)	5.46 (R31)	5.46 (R31)	5.46 (R31)	5.46 (R31)	5.46 (R31)
Walls Above Grade Minimum RSI (R)-Value[1]	4.23 (R24)	4.75 (R27)	4.75 (R27)	4.23 (R24)	4.23 (R24)	4.23 (R24)	4.23 (R24)	4.23 (R24)	3.87 (R22)	3.87 (R22)	3.87 (R22)	4.23 (R24)	4.23 (R24)
Basement Walls Minimum RSI (R)-Value[1]	3.52 (R20)	3.52 (R20)	3.52 (R20)	3.52 (R20)	3.52 (R20)	2.11 (R12)	2.11 (R12)	2.11 (R12)	3.52 (R20)	2.11 (R12)	3.87 (R22)	3.87 (R22)	3.52 (R20)
Below Grade Slab Entire surface > 600 mm below grade Minimum RSI (R)-Value[1]	0.88 (R5)	—	—	—	—	—	—	—	—	—	—	—	—
Edge of Below Grade Slab ≤ 600 mm Below Grade Minimum RSI (R)-Value[1]	1.76 (R10)	1.76 (R10)	1.76 (R10)	1.76 (R10)	1.76 (R10)	1.76 (R10)	1.76 (R10)	1.76 (R10)	1.76 (R10)	1.76 (R10)	1.76 (R10)	1.76 (R10)	1.76 (R10)
Heated Slab or Slab ≤ 600 mm below grade Minimum RSI (R)-Value[1]	1.76 (R10)	1.76 (R10)	1.76 (R10)	1.76 (R10)	1.76 (R10)	1.76 (R10)	1.76 (R10)	1.76 (R10)	1.76 (R10)	1.76 (R10)	1.76 (R10)	1.76 (R10)	1.76 (R10)
Windows and Sliding Glass Doors Maximum U-Value[2]	1.6	1.6	1.8	1.8	1.8	1.8	1.8	2.0	1.8	1.8	1.8	1.8	1.8
Skylights Maximum U-Value[2]	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8
Space Heating Equipment Minimum AFUE	90%	90%	94%	94%	90%	94%	92%	94%	92%	94%	90%	94%	90%[8]
HRV[6,7] Minimum Efficiency	—	—	—	—	55%	60%	60%	70%	55%	60%	—	—	—
Domestic Hot Water Heater Minimum EF	0.57	0.57	0.62	0.67	0.57	0.57	0.62	0.67	0.62	0.67	0.57	0.57	0.80[8]
Column 1	2	3	4	5	6	7	8	9	10	11	12	13	14

Notes to Table 2.1.1.2.A:

(1) Except for notes (3) and (4), the values listed are minimum RSI-Values for the thermal insulation component only. RSI-Values are expressed in (m²·K)/W.
(2) U-Value is the overall coefficient of heat transfer expressed in W/(m²·K).
(3) Compliance package K applies only to a *building* with both ICF *basement* walls and ICF above grade walls. Alternatively, any other compliance package is permitted to be used for a *building* with both ICF *basement* walls and ICF above grade walls. The thermal resistance value of an ICF wall is the total thermal resistance of the entire wall assembly.
(4) Compliance package L applies only to a *building* with ICF *basement* walls. Alternatively, any other compliance package except compliance package K, is permitted to be used for a *building* with ICF *basement* walls. The thermal resistance value of an ICF wall is the total thermal resistance of the entire wall assembly.
(5) Applies to a *building* with combined space heating and domestic hot water heating system.
(6) Except as required in Subsection 9.32.3. of Division B in the *Building Code*, an HRV is only required as a part of the compliance package where a minimum efficiency level is specified.
(7) The minimum efficiency of an HRV shall be based on a test temperature of 0°C. In addition, where an HRV is installed to meet the requirements of Subsection 9.32.3. of Division B in the *Building Code*, the energy efficiency of the HRV shall also meet the minimum efficiency requirements of Sentence 9.32.3.11.(2).
(8) Only the hot water heating equipment shall meet the minimum AFUE or EF specified in the Table or shall be of the condensing type.

Table 2: OBC Supplementary Standard SB 12

Appendix B: WUFI modelling (Literature)

WUFI is a Windows-based program designed to calculate the simultaneous heat and moisture transport in one dimensional multi-layered building components for a wide range of building material classes and climatic conditions (Kunzel, 1995).

Hygrothermal simulation of this nature is to be viewed just as a comparative tool. The results presented from WUFI simulations developed from educated estimates, average weather conditions, and possibly various material defaults within the software. Most of the time, the results portrayed by WUFI rather should be used just as comparative to the baseline wall assemblies, because it doesn't represent exact anticipated conditions, as an industry standard.

1. **Calculation Model**

For calculation, the differential equations presented below (moisture and heat balance) are discretised by means of an implicit finite volume method. Solving process follows iteration of the flow chart illustrated below (Figure 1). Size of the mesh, time step and convergence criteria influence the accuracy of the numerical solution. Effect of numerical parameters is usually not significant in comparison with the effects of the physical parameters like materials and climate data (Evard, 2008). Results should always be critically assessed in order to exclude user errors or severe convergence errors (quantify by WUFI). While modeling in WUFI, many assumptions are to be made and boundary conditions are to be defined. Similarly, a series of sensitivity analyses to be necessary to carried out to test assumptions and to identify the impacts of such assumptions (Kunzel, 1995). WUFI model only allow to input a single sorption curve (no difference between sorption and desorption process) (Evard, 2008).

The simplified model for WUFI is written numerically (as shown below) and solves by WUFI itself.

Moisture balance

$$\vec{\nabla}(C_{M1}\nabla\theta + C_{M2}\nabla\phi) \pm S_M = B_{M2}(\delta\phi/\delta t)$$

At teach time step, conservation of mass and energy can be used to write the moisture variation δw, as

$$\frac{\delta w}{\delta t} = \xi_\phi . \frac{\delta \phi}{\delta t} = \vec{\nabla}(-D_\phi . \nabla\phi - \delta . \nabla(\phi . P_{sat}))$$

Heat balance

$$\vec{\nabla}(C_{H1}\nabla\theta + C_{H2}\nabla\phi) \pm S_H = B_{H1}(\delta\theta/\delta t) + B_{H2}(\delta\phi/\delta t)$$

At teach time step, conservation of mass and energy can be used to write the enthalpy variation δh, as

$$\frac{\delta h}{\delta t} = \frac{dh_w}{d\theta} \cdot \frac{\delta\theta}{\delta t} = \vec{\nabla}(-\lambda^* . \nabla\theta) + h_{vap}(\delta . \nabla(\phi . P_{sat}))$$

(Kunzel, as cited in Evard, 2008; Ferreira, 2015)

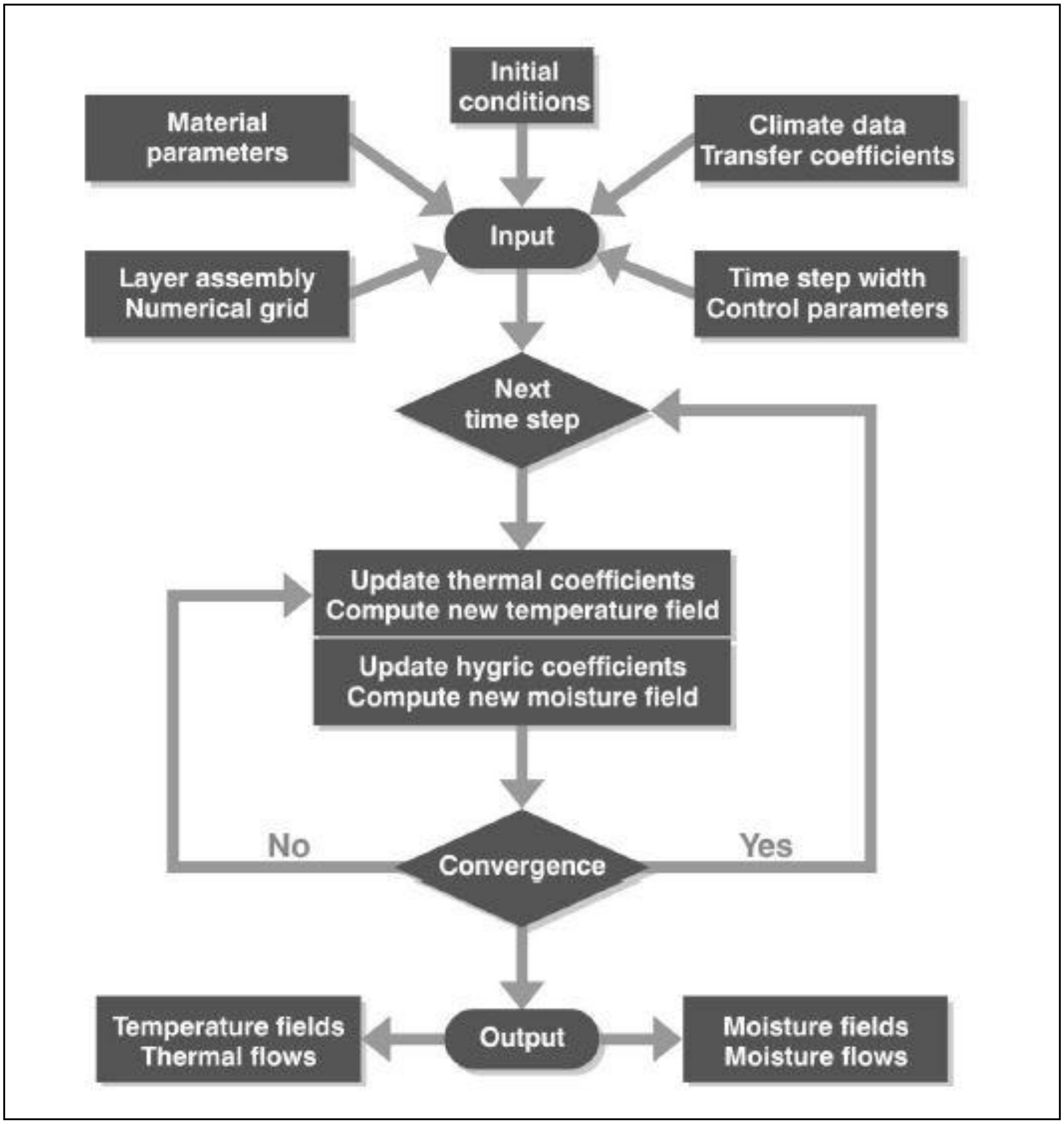


Figure 1: Flow Chart for WUFI Model

(Kunzel, 1995)

2. Material Inputs

The basic material parameters that needed as a minimum to input a new material in the database and achieve simulations are (Kunzel, 1995):

Relative to dry state:

1. Bulk density [kg/m^3]
2. Total porosity [m^3/m^3]: to define the maximal water content
3. Specific heat capacity [J/kg.K]
4. Thermal conductivity [W/m.K]
5. Water vapour diffusion resistance factor [-]

Some "hygric extensions" are not mathematically required, but are necessary to describe accurately the hygrothermal behaviour of a component:

Relative to moist state:

1. Moisture Retention Curve [kg/m3]: as a table or approximated by sorption moisture at 80% RH (w_{80}) and free saturation (w_f)
2. Moisture-dependent vapour diffusion resistance factor [-] only if no liquid transfer is used
3. Liquid transport coefficient for suction [m^2/s]: as a table or generated from the water absorption coefficient (A Value)
4. Liquid transport coefficient for redistribution [m^2/s]: as a table or generated from the water absorption coefficient (A Value)
5. Moisture-dependent thermal conductivity [W/mK]: as a table or generated from the moisture-induced thermal conductivity supplement (b)

3. Climate File

The following climate data (from climate files) for each time step will be essential:

1. The rain load vertically incident on the exterior surface in [Ltr/m^{2}h] (to determine the rain load, the inclination and orientation of the surface must be taken into account).
2. The solar radiation vertically incident on the exterior surface in [W/m^2] (to determine the amount of radiation, the inclination and orientation of the surface must be taken into account).
3. Exterior air temperature [°C] and RH [%]
4. Interior air temperature [°C] and RH [%]

5. Barometric pressure in [hPa] (the barometric pressure has only a minor effect on the calculation, specification of a mean value over the calculation period may be sufficient)
6. The long-wave atmospheric counter radiation [W/m²](if radiation cooling is to be accounted for during the night) (Evard, 2008).

4. Assessment of the results

Primary assessments in WUFI will be for

1. Total WC
2. WC in individual layers
3. Temperature and Dew point at monitoring positions
4. Temperature and RH at monitoring positions
5. Isopleths at monitoring positions
6. Film

Total WC demonstrates the behavior of moisture whether accumulated or dried out during the simulation period and thus is the main measure for assessing the results. High level of WC at one point or increasing continuously and taking long time to reach dynamic steady state may cause harm to the assemblies in the form of mould growth, rot, corrosion, freeze thaw and salt damage (reducing permeability of material by clogging the pores), heat loss etc. If it decreases below the initial condition (with high RH), considered to be the construction is dried out. Further, in the condition if WC maintains constant pattern of seasonal fluctuations, the assembly is considered to be reached in the dynamic steady state. This state is the basis for assessment, which evidences the behavior of assemblies under the applied climatic conditions. In addition, WC of all the individual layers have also be analyzed (moisture accumulation < 20%mass for wood based material in each layer) and verified whether they have reached the dynamic equilibrium level (Zirkelbach et al, 1995).

Dew point should be substantially below the temperature and show a regular pattern of seasonal fluctuation at each monitoring position, otherwise condensation can take place. WC and dew point can yield where condensation is likely to occur. Similarly, RH and temperature graphs and Isopleths (RH at each 1 hour time step against the respective temperature) at every monitoring position has to be analyzed, which manifests whether high RH and high temperature occur at same time; will be potential to mold growth. Isopleths should always stay below the dotted (for hygroscopic material) curve so that any risk of mould growth can be avoided

(Zirkelbach et al, 1995). In this regard, Viitanen et al (2010) states that for mould growth, the minimum (critical) ambient humidity has to be between RH 80 - 95 % depending on other factors like ambient temperature, exposure time, quality and surface conditions of building materials and for decay development, the critical humidity is above 95% RH.

WUFI film, on the other hand is ideal to develop the feel for the reactions of components under different climactic conditions, and provides information on the how the wall conditions change throughout the simulation period. It shows the progress in the time of the temperature, dew point, RH and WC along with moisture and heat fluxes across the interfaces layer and the component surfaces. Solar radiation and rain are also showed in the film window. Ultimately, the film is useful for gaining insight into the overall hygrothermal processes in each and overall component (Zirkelbach et al, 1995).

Appendix C: Detail Results (Laboratory test)

This section presents the summary of laboratory test results.

1. **Evolution of densities during drying**

Mix	Day 0 (Initial) (11/18/2015)					Day 26 (12/14/2015)							
	Net Mass (g)		Density (kg/m3)	Mean Density (kg/m3)		Net Mass (g)		Density (kg/m3)	Mean Density (kg/m3)	Change in Mass (g)	Change in Density/Mass	
											Preceding Day	Initial	
1	3459.85	14813.86	488.25	491.89		1920.00	8406.00	270.95	279.12	-28.00	-0.33%	-43.26%	
	3108.88		438.72			1750.00		246.96					
	3047.51		430.06			1714.00		241.88					
	2016.51		569.14			1156.00		326.27					
	1756.79		590.28			1034.00		347.42					
	1424.32		609.09			832.00		355.79					
2	4300.55	17297.95	606.89	574.37		2766.00	11158.00	390.34	370.50	-28.00	-0.25%	-35.50%	
	4197.81		592.39			2690.00		379.61					
	4091.06		577.33			2544.00		359.01					
	1919.76		541.83			1380.00		389.49					
	1533.93		515.40			990.00		332.64					
	1254.83		536.61			788.00		336.98					
3	4817.02	21013.83	679.78	697.76		3076.00	13850.00	434.09	459.89	-28.00	-0.20%	-34.09%	
	4907.76		692.58			3190.00		450.17					
	4825.02		680.91			3114.00		439.45					
	2633.72		743.34			1846.00		521.02					
	2035.02		683.77			1404.00		471.74					
	1795.30		767.74			1220.00		521.72					

Table 1: Day 0 (initial) and Day 26 (minimum) densities during drying

2. Dry Densities

Dry and Cool											
Mix	Sample	Length	Width	Height	Volume (m3)		Mass (g)	Total Mass (g)	Density (kg/m3)	Mean Density (kg/m3)
1	1AK1	30.3000	30.3000	7.6863	0.0070567	0.0261036	1660.00	6083.00	235.24	233.03
	1AK2	30.3000	30.3000	7.6174	0.0069935		1546.00		221.06	
	1AK3	30.3000	30.3000	7.5117	0.0068964		1506.00		218.37	
	1A-1	7.8800	7.6225	7.6175	0.0004575		114.00		249.15	
	1A-2	7.4580	7.5560	7.5495	0.0004254		116.00		272.66	
	1B-1	7.3665	7.6895	7.4115	0.0004198		128.00		304.89	
	1B-2	7.4455	7.4865	7.5130	0.0004188		117.00		279.38	
	1C-1	7.5295	7.6315	7.6590	0.0004401		139.00		315.84	
	1C-2	7.6695	7.6385	7.7005	0.0004511		122.00		270.44	
	A1	7.9670	7.4900	6.9160	0.0004127		96.00		232.62	
	A2	7.5540	7.8960	7.4110	0.0004420		118.00		266.94	
	A3	7.4320	7.6550	7.4310	0.0004228		104.00		246.00	
	A4	7.4210	7.6790	7.5410	0.0004297		114.00		265.28	
	A5	7.5500	7.6150	7.4260	0.0004269		110.00		257.64	
	A6	7.5590	7.4490	7.3890	0.0004161		93.00		223.53	
2	2AK1	30.3000	30.3000	7.7567	0.0071213	0.0266079	2346.00	8429.00	329.43	316.79
	2AK2	30.3000	30.3000	7.8302	0.0071888		2286.00		317.99	
	2AK3	30.3000	30.3000	7.6748	0.0070462		2216.00		314.50	
	2A-1	7.6715	7.6595	7.6685	0.0004506		127.00		281.85	
	2A-2	7.6560	7.5755	7.6870	0.0004458		144.00		322.99	
	2B-1	7.6555	7.4460	7.6705	0.0004372		138.00		315.62	
	2B-2	7.6725	7.4490	7.6730	0.0004385		122.00		278.20	
	2C-1	7.6870	7.6790	7.6870	0.0004538		129.00		284.30	
	2C-2	7.7035	7.4395	7.4220	0.0004254		129.00		303.28	
	B1	7.6780	7.6600	7.4190	0.0004363		148.00		339.19	
	B2	7.8010	7.7650	7.4460	0.0004510		138.00		305.96	
	B3	7.6810	7.6980	7.6920	0.0004548		124.00		272.64	
	B4	7.4200	7.6350	7.5980	0.0004304		117.00		271.82	
	B5	7.4430	7.5100	7.4600	0.0004170		133.00		318.95	
	B6	7.4210	7.4490	7.4280	0.0004106		132.00		321.47	
3	3AK1	30.3000	30.3000	7.8260	0.0071850	0.0266933	2800.00	10350.00	389.70	387.74
	3AK2	30.3000	30.3000	7.7240	0.0070913		2710.00		382.16	
	3AK3	30.3000	30.3000	7.8025	0.0071634		2680.00		374.12	
	3A-1	7.6165	7.6570	7.6610	0.0004468		178.00		398.40	
	3A-2	7.7175	7.6765	7.6880	0.0004555		208.00		456.68	

	3B-1	7.6720	7.4380	7.6945	0.0004391		170.00		387.17	
	3B-2	7.6850	7.6950	7.7085	0.0004559		170.00		372.93	
	3C-1	7.6665	7.6635	7.6930	0.0004520		190.00		420.37	
	3C-2	7.4980	7.6855	7.4745	0.0004307		192.00		445.76	
	C1	7.5830	7.4800	7.5970	0.0004309		184.00		427.01	
	C2	7.8110	7.4920	7.4080	0.0004335		188.00		433.66	
	C3	7.6640	7.5120	7.4490	0.0004289		168.00		391.74	
	C4	7.3810	7.6100	7.3980	0.0004155		158.00		380.23	
	C5	7.4640	7.5570	7.4450	0.0004199		191.00		454.83	
	C6	7.4510	7.7700	7.6850	0.0004449		163.00		366.36	

Table 2: Dry Densities

3. Free Water Saturation (W_f)

Cold Water submersion for 48 hours

Mix	Volume (m3)	Dry Mass (g)		Submerse (48 hours)				
				Mass (g)		Difference (g)		MC
		Individual	Total	Individual	Total	Individual	Total	(kg/m3)
1	0.002171	114.00	597.00	274.00	1414.00	160.00	817.00	376.29
		116.00		270.00		154.00		
		128.00		295.00		167.00		
		117.00		282.00		165.00		
		122.00		293.00		171.00		
2	0.002198	127.00	660.00	288.00	1484.00	161.00	824.00	374.96
		144.00		315.00		171.00		
		138.00		306.00		168.00		
		122.00		285.00		163.00		
		129.00		290.00		161.00		
3	0.002224	178.00	938.00	367.00	1880.00	189.00	942.00	423.55
		208.00		408.00		200.00		
		170.00		348.00		178.00		
		190.00		370.00		180.00		
		192.00		387.00		195.00		

Table 3: MC at 48 hours submersion in cold water

4. Maximum Water Content (W_{max})

i. Boiling the samples immediately after cold water submersion for 48 hours

Mix	Volume (m3)	Dry Mass (g)		Boiling and Natural Cooling for 48 hours				
				Mass (g)		Difference (g)		MC
		Individual	Total	Individual	Total	Individual	Total	(kg/m3)
1	0.002171	114.00	597.00	338.00	1724.00	224.00	1127.00	519.07
		116.00		340.00		224.00		
		128.00		370.00		242.00		
		117.00		348.00		231.00		
		122.00		328.00		206.00		
2	0.002198	127.00	660.00	353.00	1803.00	226.00	1143.00	520.12
		144.00		391.00		247.00		
		138.00		378.00		240.00		
		122.00		325.00		203.00		
		129.00		356.00		227.00		
3	0.002224	178.00	938.00	462.00	2394.00	284.00	1456.00	654.67
		208.00		517.00		309.00		
		170.00		445.00		275.00		
		190.00		484.00		294.00		
		192.00		486.00		294.00		

Table 4: MC at 5 hour boiling and 48 hours natural cooling

ii. Boiling dry samples

Mix	Volume (m3)	Dry Mass (g)		Boiling and Natural Cooling for 48 hours				
				Mass (g)		Difference (g)		MC
		Individual	Total	Individual	Total	Individual	Total	(kg/m3)
1	0.002133	95.00	538.00	303.00	1674.00	208.00	1136.00	532.66
		115.00		357.00		242.00		
		104.00		326.00		222.00		
		114.00		352.00		238.00		
		110.00		336.00		226.00		
2	0.002190	149.00	662.00	383.00	1813.00	234.00	1151.00	525.66
		139.00		388.00		249.00		
		125.00		359.00		234.00		
		116.00		320.00		204.00		
		133.00		363.00		230.00		
3	0.002129	184.00	893.00	466.00	2288.00	282.00	1395.00	655.31
		188.00		478.00		290.00		
		170.00		452.00		282.00		
		159.00		416.00		257.00		
		192.00		476.00		284.00		

Table 5: MC at 5 hour boiling and 48 hours natural cooling

Appendix D: Detail Results (WUFI modelling)

This section presents the summary of simulation results.

1. Climate/ Orientation

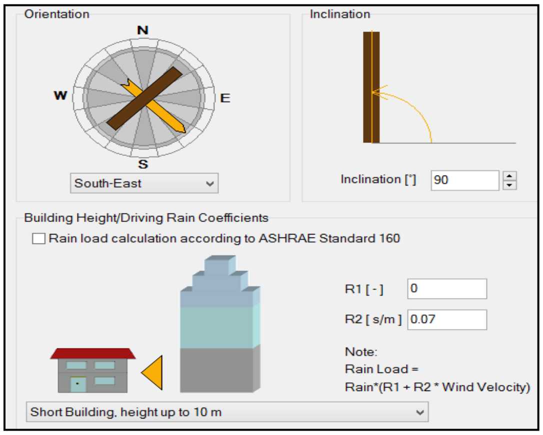


Figure 1: Orientation

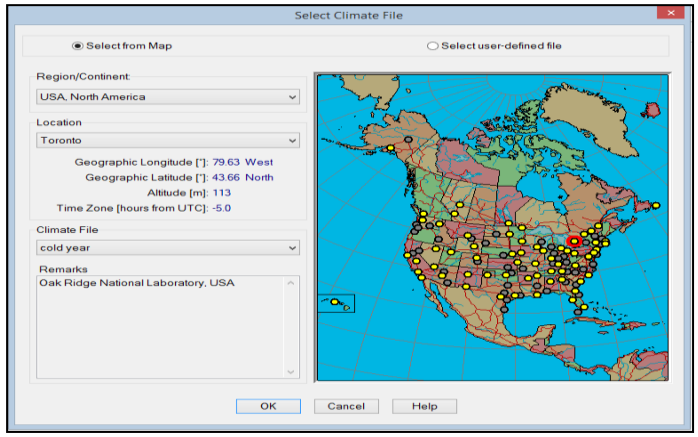


Figure 2: Map File

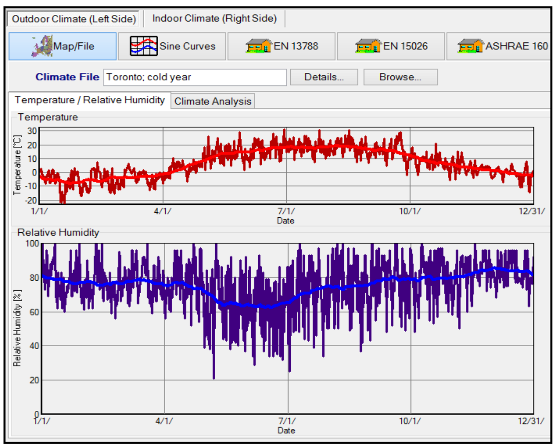


Figure 3: Outdoor Climate

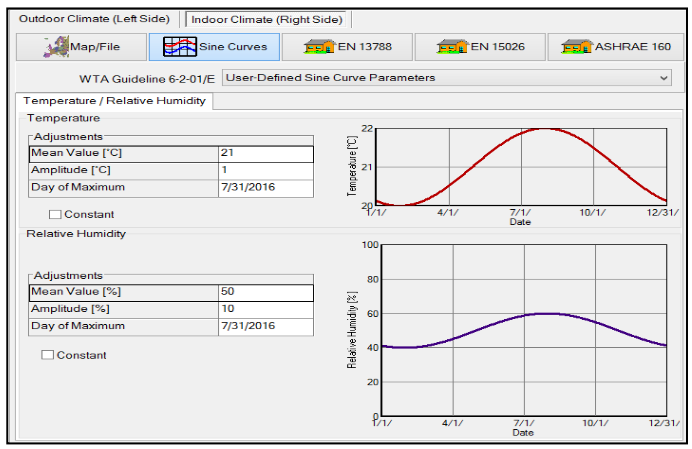


Figure 4: Indoor Climate

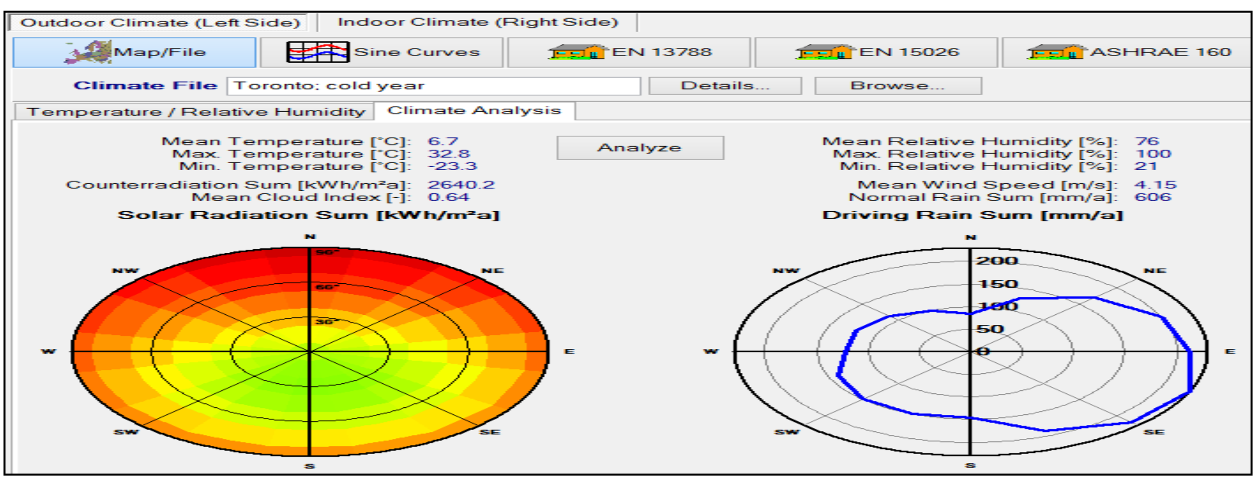
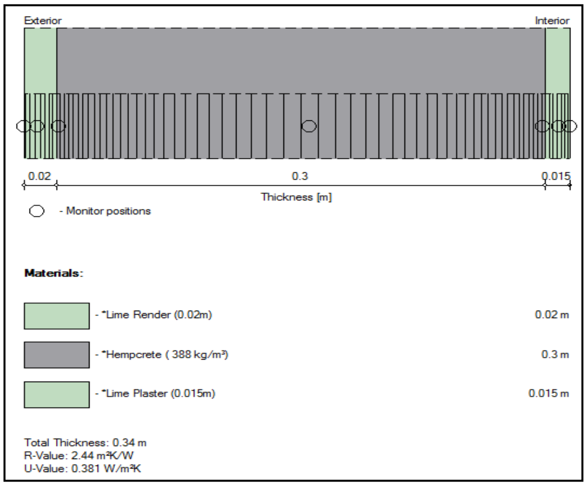


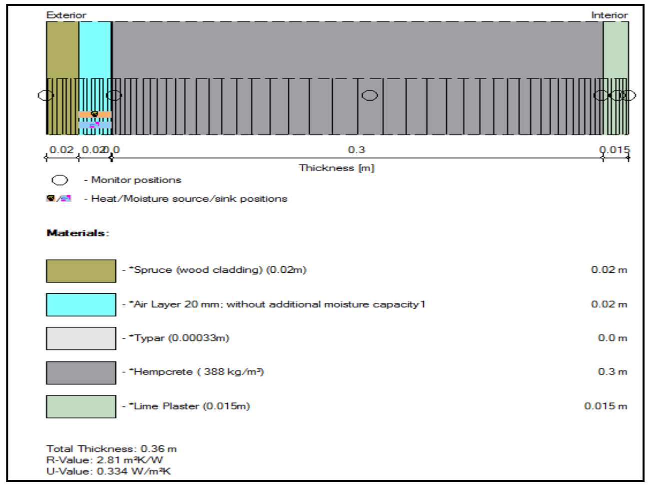
Figure 5: Radiation and Rain Flowers

2. Assemblies

A. Base Cases



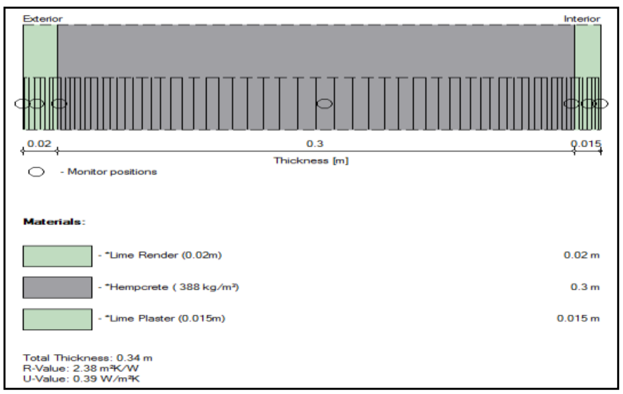
Assembly 1



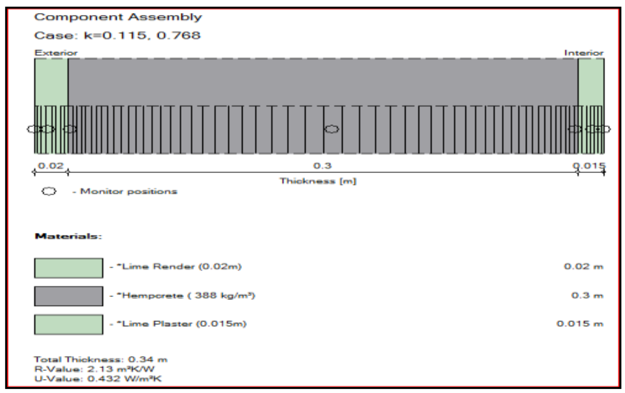
Assembly 2

Figure 6: Base Case Assemblies

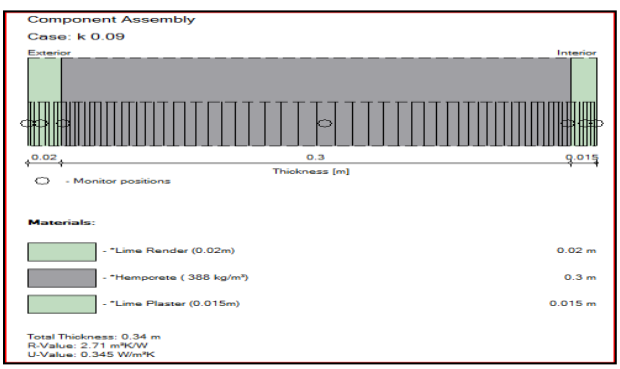
B. Sensitivity Analysis



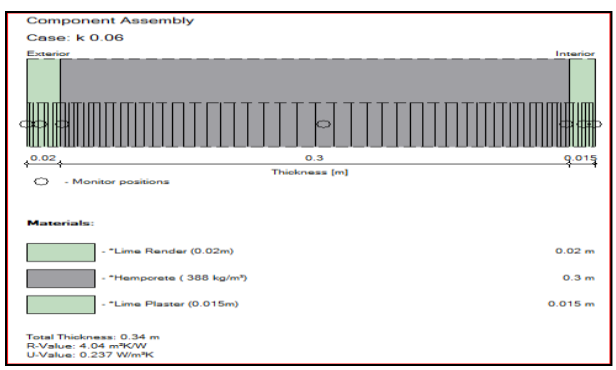
Sensitivity Analysis 1



Sensitivity Analysis 2



Sensitivity Analysis 3



Sensitivity Analysis 4

Figure 7: Sensitivity Analysis

3. Surface Transfer Coefficients

Exterior (Left Side)
Location: Toronto; cold year
Orientation / Inclination: South-East / 90 °

Interior (Right Side)
Indoor Climate: WTA Guideline 6-2-01/E
User-Defined Sine Curve Parameters

Surface Transfer Coefficients

Exterior (Left Side)

Name	Description	Unit	Value
Heat Resistance - includes long-wave radiation	External Wall	[m²K/W]	0.0588 yes
Sd-Value	No coating	[m]	----
Short-Wave Radiation Absorptivity	Limestone, bright	[-]	0.4
Long-Wave Radiation Emissivity	Limestone, bright	[-]	0.9
Adhering Fraction of Rain	Depending on inclination of co	[-]	0.7
Explicit Radiation Balance			yes
Terrestrial Short-Wave Reflectivity		[-]	0.20
Terrestrial Long-Wave Emissivity		[-]	0.9
Terrestrial Long-Wave Reflectivity		[-]	0.1
Cloud Index		[-]	0.64

Interior (Right Side)

Name	Description	Unit	Value
Heat Resistance	External Wall	[m²K/W]	0.125
Sd-Value	No coating	[m]	----

Table 1: Surface Transfer Coefficients (Assembly1)

Exterior (Left Side)
Location: Toronto; cold year
Orientation / Inclination: South-East / 90 °

Interior (Right Side)
Indoor Climate: WTA Guideline 6-2-01/E
User-Defined Sine Curve Parameters

Surface Transfer Coefficients

Exterior (Left Side)

Name	Description	Unit	Value
Heat Resistance - includes long-wave radiation	External Wall	[m²K/W]	0.0588 yes
Sd-Value	No coating	[m]	----
Short-Wave Radiation Absorptivity	Wood (spruce):untreated	[-]	0.4
Long-Wave Radiation Emissivity	Wood (spruce):untreated	[-]	0.9
Adhering Fraction of Rain	Depending on inclination of co	[-]	0.7
Explicit Radiation Balance			yes
Terrestrial Short-Wave Reflectivity		[-]	0.2
Terrestrial Long-Wave Emissivity		[-]	0.9
Terrestrial Long-Wave Reflectivity		[-]	0.1
Cloud Index		[-]	0.64

Interior (Right Side)

Name	Description	Unit	Value
Heat Resistance	External Wall	[m²K/W]	0.125
Sd-Value	No coating	[m]	----

Table 2: Surface Transfer Coefficients (Assembly 2)

Sources, Sinks

***Air Layer 20 mm; without additional moisture capacity1**

Name	Type		
Source1	*Air Change Source*		
	Whole Layer		
	mix with air from left-hand side		
	Air Changes	[1/h]	8

Table 3: Sources and Sink (Assembly 2)

4. Materials Data

Material: *Hempcrete (388 kg/m³)

Checking Input Data

Property	Unit	Value
Bulk density	[kg/m³]	388.0
Porosity	[m³/m³]	0.66
Specific Heat Capacity, Dry	[J/kgK]	1560.0
Thermal Conductivity, Dry, 10°C	[W/mK]	0.1
Water Vapour Diffusion Resistance Factor	[-]	4.85
Reference Water Content	[kg/m³]	29.0
Free Water Saturation	[kg/m³]	424.0
Water Absorption Coefficient	[kg/m²s^0.5]	0.074
Moisture-dep. Thermal Cond. Supplement	[%/M.-%]	3.34
Temp-dep. Thermal Cond. Supplement	[W/mK²]	0.0002

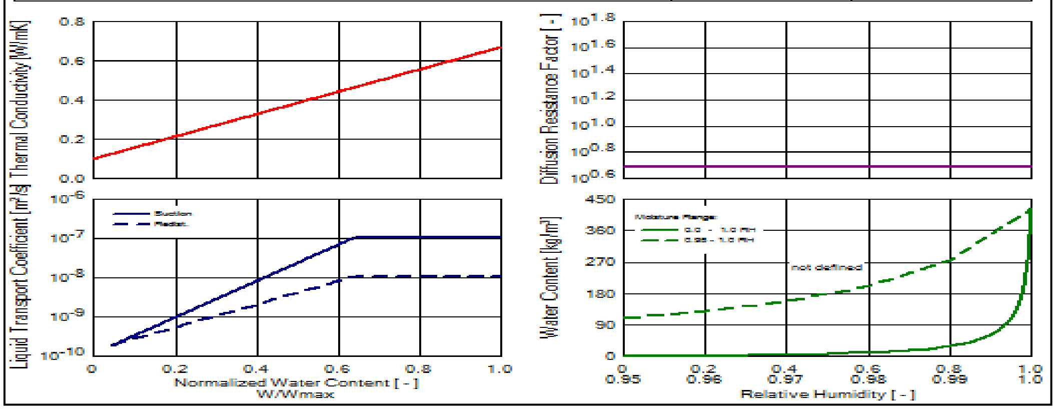
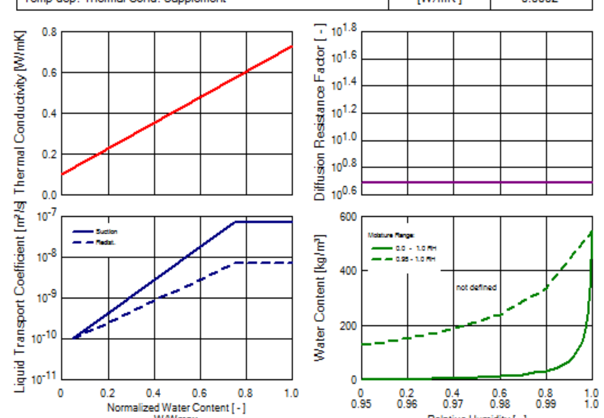


Figure 8: Hempcrete (Assembly 1 and 2)

Material: *Hempcrete (388 kg/m³)

Checking Input Data

Property	Unit	Value
Bulk density	[kg/m³]	388.0
Porosity	[m³/m³]	0.73
Specific Heat Capacity, Dry	[J/kgK]	1560.0
Thermal Conductivity, Dry, 10°C	[W/mK]	0.1
Water Vapour Diffusion Resistance Factor	[-]	4.85
Reference Water Content	[kg/m³]	33.0
Free Water Saturation	[kg/m³]	546.0
Water Absorption Coefficient	[kg/m²s^0.5]	0.074
Moisture-dep. Thermal Cond. Supplement	[%/M.-%]	3.34
Temp-dep. Thermal Cond. Supplement	[W/mK²]	0.0002

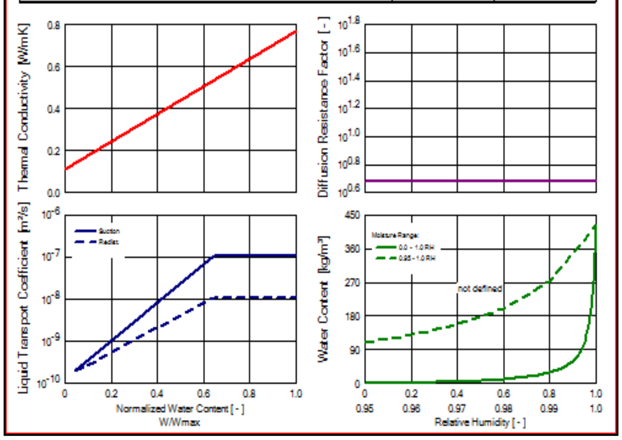


Sensitivity Analysis 1

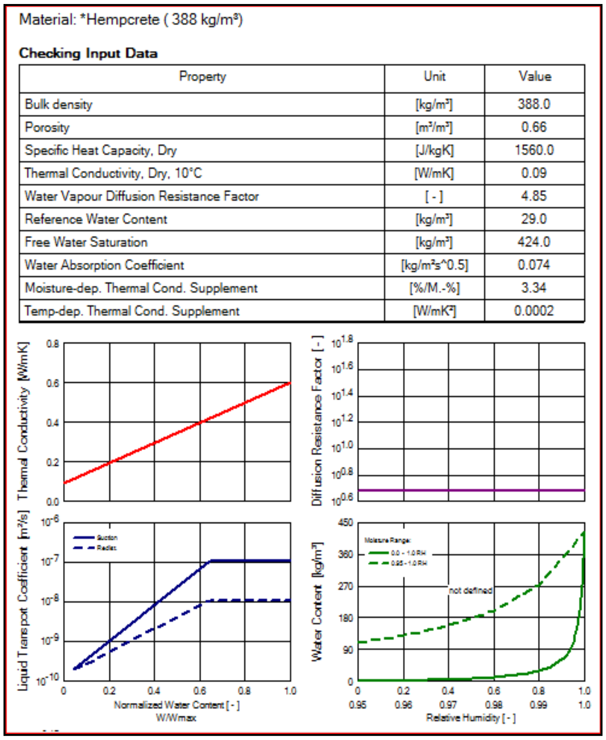
Material: *Hempcrete (388 kg/m³)

Checking Input Data

Property	Unit	Value
Bulk density	[kg/m³]	388.0
Porosity	[m³/m³]	0.66
Specific Heat Capacity, Dry	[J/kgK]	1560.0
Thermal Conductivity, Dry, 10°C	[W/mK]	0.115
Water Vapour Diffusion Resistance Factor	[-]	4.85
Reference Water Content	[kg/m³]	29.0
Free Water Saturation	[kg/m³]	424.0
Water Absorption Coefficient	[kg/m²s^0.5]	0.074
Temp-dep. Thermal Cond. Supplement	[W/mK²]	0.0002



Sensitivity Analysis 2

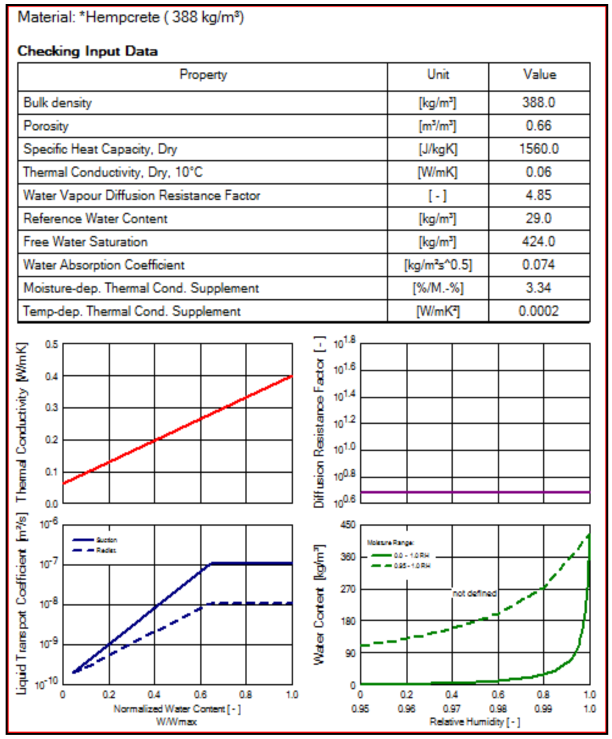


Material: *Hempcrete (388 kg/m³)

Checking Input Data

Property	Unit	Value
Bulk density	[kg/m³]	388.0
Porosity	[m³/m³]	0.66
Specific Heat Capacity, Dry	[J/kgK]	1560.0
Thermal Conductivity, Dry, 10°C	[W/mK]	0.09
Water Vapour Diffusion Resistance Factor	[-]	4.85
Reference Water Content	[kg/m³]	29.0
Free Water Saturation	[kg/m³]	424.0
Water Absorption Coefficient	[kg/m²s^0.5]	0.074
Moisture-dep. Thermal Cond. Supplement	[%/M.-%]	3.34
Temp-dep. Thermal Cond. Supplement	[W/mK²]	0.0002

Sensitivity Analysis 3



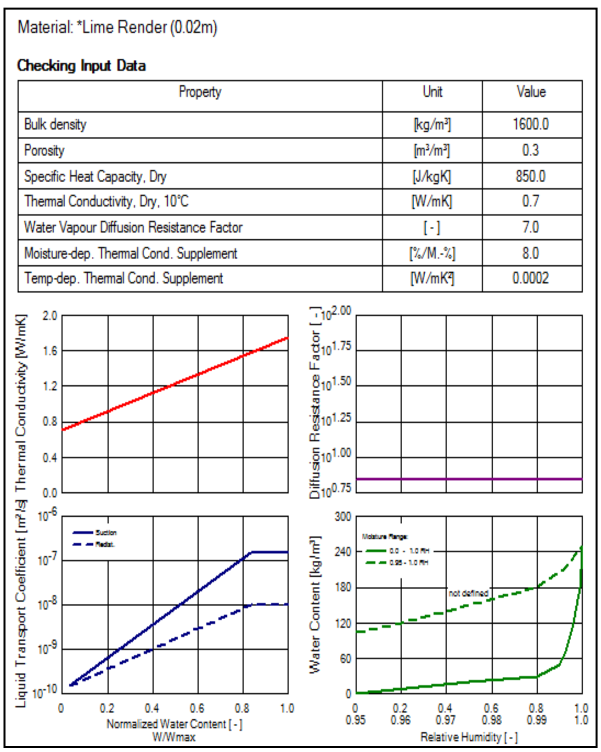
Material: *Hempcrete (388 kg/m³)

Checking Input Data

Property	Unit	Value
Bulk density	[kg/m³]	388.0
Porosity	[m³/m³]	0.66
Specific Heat Capacity, Dry	[J/kgK]	1560.0
Thermal Conductivity, Dry, 10°C	[W/mK]	0.06
Water Vapour Diffusion Resistance Factor	[-]	4.85
Reference Water Content	[kg/m³]	29.0
Free Water Saturation	[kg/m³]	424.0
Water Absorption Coefficient	[kg/m²s^0.5]	0.074
Moisture-dep. Thermal Cond. Supplement	[%/M.-%]	3.34
Temp-dep. Thermal Cond. Supplement	[W/mK²]	0.0002

Sensitivity Analysis 4

Figure 9: Hempcrete (Sensitivity Analysis)

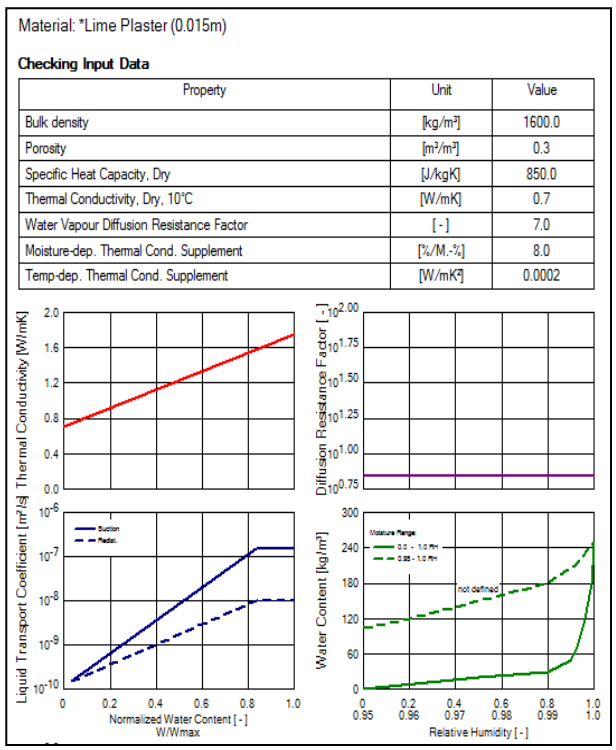


Material: *Lime Render (0.02m)

Checking Input Data

Property	Unit	Value
Bulk density	[kg/m³]	1600.0
Porosity	[m³/m³]	0.3
Specific Heat Capacity, Dry	[J/kgK]	850.0
Thermal Conductivity, Dry, 10°C	[W/mK]	0.7
Water Vapour Diffusion Resistance Factor	[-]	7.0
Moisture-dep. Thermal Cond. Supplement	[%/M.-%]	8.0
Temp-dep. Thermal Cond. Supplement	[W/mK²]	0.0002

Figure 10: Lime Render

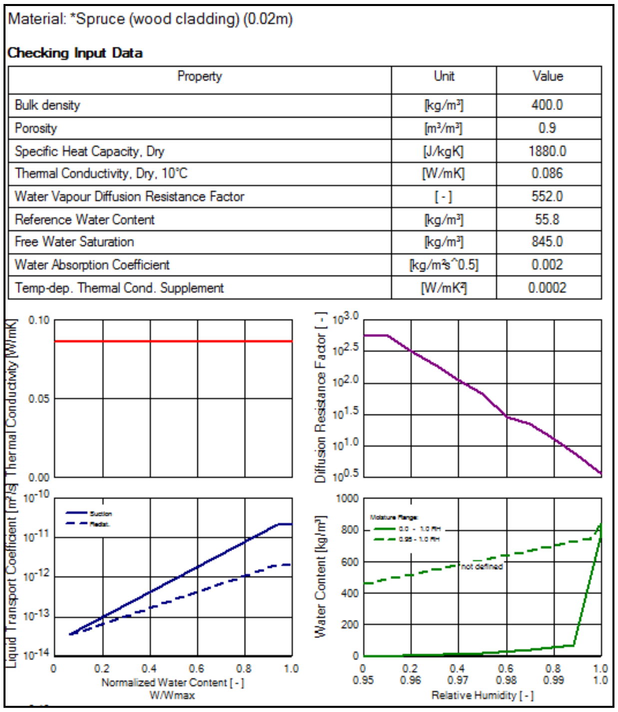


Material: *Lime Plaster (0.015m)

Checking Input Data

Property	Unit	Value
Bulk density	[kg/m³]	1600.0
Porosity	[m³/m³]	0.3
Specific Heat Capacity, Dry	[J/kgK]	850.0
Thermal Conductivity, Dry, 10°C	[W/mK]	0.7
Water Vapour Diffusion Resistance Factor	[-]	7.0
Moisture-dep. Thermal Cond. Supplement	[%/M.-%]	8.0
Temp-dep. Thermal Cond. Supplement	[W/mK²]	0.0002

Figure 11: Lime Plaster

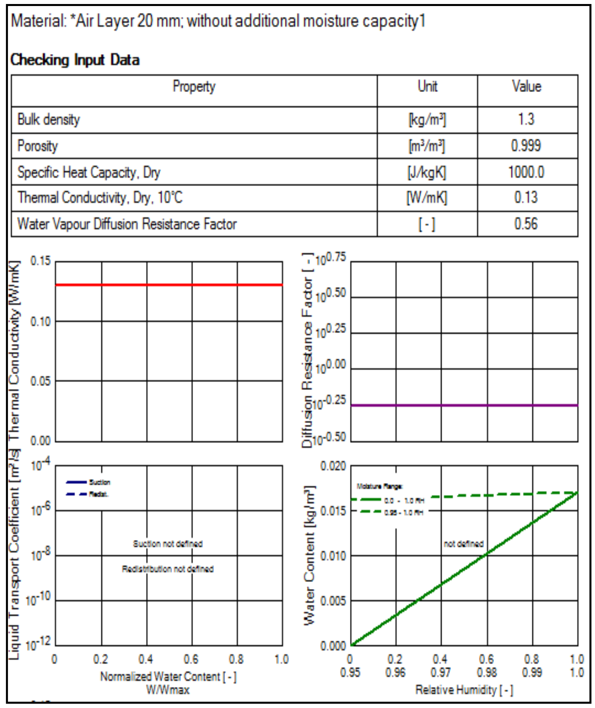


Material: *Spruce (wood cladding) (0.02m)

Checking Input Data

Property	Unit	Value
Bulk density	[kg/m³]	400.0
Porosity	[m³/m³]	0.9
Specific Heat Capacity, Dry	[J/kgK]	1880.0
Thermal Conductivity, Dry, 10°C	[W/mK]	0.086
Water Vapour Diffusion Resistance Factor	[-]	552.0
Reference Water Content	[kg/m³]	55.8
Free Water Saturation	[kg/m³]	845.0
Water Absorption Coefficient	[kg/m²s^0.5]	0.002
Temp-dep. Thermal Cond. Supplement	[W/mK²]	0.0002

Figure 12: Wood Cladding (Spruce)

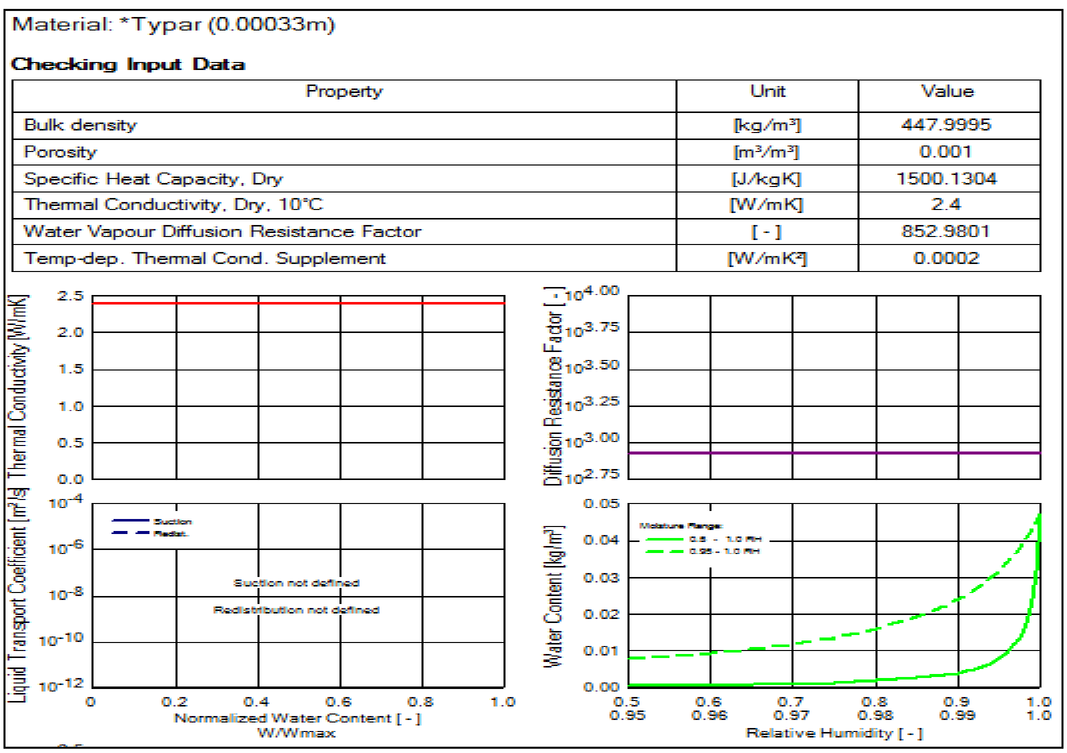


Material: *Air Layer 20 mm; without additional moisture capacity1

Checking Input Data

Property	Unit	Value
Bulk density	[kg/m³]	1.3
Porosity	[m³/m³]	0.999
Specific Heat Capacity, Dry	[J/kgK]	1000.0
Thermal Conductivity, Dry, 10°C	[W/mK]	0.13
Water Vapour Diffusion Resistance Factor	[-]	0.56

Figure 13: Air Layer



Material: *Typar (0.00033m)

Checking Input Data

Property	Unit	Value
Bulk density	[kg/m³]	447.9995
Porosity	[m³/m³]	0.001
Specific Heat Capacity, Dry	[J/kgK]	1500.1304
Thermal Conductivity, Dry, 10°C	[W/mK]	2.4
Water Vapour Diffusion Resistance Factor	[-]	852.9801
Temp-dep. Thermal Cond. Supplement	[W/mK²]	0.0002

Figure 14: Typar

5. Results from last calculations

Status of Calculation

Calculation: Time and Date	1/12/2016 4:21:42 PM
Computing Time	5 min,38 sec.
Begin / End of calculation	10/1/2015 / 10/1/2018
No. of Convergence Failures	11

Check for numerical quality

Integral of fluxes, left side (kl,dl)	$[kg/m^2]$	77.59 -76.76
Integral of fluxes, right side (kr,dr)	$[kg/m^2]$	0.31 2.3
Balance 1	$[kg/m^2]$	-1.78
Balance 2	$[kg/m^2]$	-1.78

Water Content $[kg/m^2]$

	Start	End	Min.	Max.
Total Water Content	9.75	7.98	7.78	17.57

Water Content $[kg/m^3]$

Layer/Material	Start	End	Min.	Max.
*Lime Render (0.02m)	30.00	28.88	17.95	228.72
*Hempcrete (388 kg/m³)	29.00	23.54	23.18	44.07
*Lime Plaster (0.015m)	30.00	22.53	17.06	30.00

Time Integral of fluxes

Heat Flux, left side	$[MJ/m^2]$	-489.01
Heat Flux, right side	$[MJ/m^2]$	-487.69
Moisture Fluxes, left side	$[kg/m^2]$	0.84
Moisture Fluxes, right side	$[kg/m^2]$	2.62

Hygrothermal Sources

Heat Sources	$[MJ/m^2]$	0.0
Moisture Sources	$[kg/m^2]$	0.0
Unreleased Moisture Sources (due to cut-off)	$[kg/m^2]$	0.0

Table 4: Assembly 1 (Base Case)

Status of Calculation

Calculation: Time and Date	1/14/2016 10:10:31 PM
Computing Time	26 min,57 sec.
Begin / End of calculation	10/1/2015 / 10/1/2018
No. of Convergence Failures	221

Check for numerical quality

Integral of fluxes, left side (kl,dl)	$[kg/m^2]$	0.75 -1.05
Integral of fluxes, right side (kr,dr)	$[kg/m^2]$	0.11 0.25
Balance 1	$[kg/m^2]$	-4.76
Balance 2	$[kg/m^2]$	-4.77

Water Content $[kg/m^2]$

	Start	End	Min.	Max.
Total Water Content	10.27	5.51	5.13	11.08

Water Content $[kg/m^3]$

Layer/Material	Start	End	Min.	Max.
*Spruce (wood cladding) (0.02m)	55.83	46.26	27.55	113.64
*Air Layer 20 mm; without additional moistur	0.01	0.01	0.01	0.02
*Typar (0.00033m)	0.00	0.00	0.00	0.01
*Hempcrete (388 kg/m³)	29.00	14.18	13.98	29.00
*Lime Plaster (0.015m)	30.00	22.19	16.76	30.00

Time Integral of fluxes

Heat Flux, left side	$[MJ/m^2]$	-377.76
Heat Flux, right side	$[MJ/m^2]$	-394.01
Moisture Fluxes, left side	$[kg/m^2]$	-0.8
Moisture Fluxes, right side	$[kg/m^2]$	0.37

Hygrothermal Sources

Heat Sources	$[MJ/m^2]$	-14.38
Source1 (Air Change Source)	$[MJ/m^2]$	-14.38
Moisture Sources	$[kg/m^2]$	-4.102

Unreleased Moisture Sources (due to cut-off)	$[kg/m^2]$	-0.0
Source1 (Air Change Source)	$[kg/m^2]$	-4.102

Table 5: Assembly 2

Status of Calculation

Calculation: Time and Date	1/21/2016 10:39:48 PM
Computing Time	7 min,10 sec.
Begin / End of calculation	10/1/2015 / 10/1/2018
No. of Convergence Failures	6

Check for numerical quality

Integral of fluxes, left side (kl,dl)	$[kg/m^2]$	76.35 -76.68
Integral of fluxes, right side (kr,dr)	$[kg/m^2]$	0.26 1.67
Balance 1	$[kg/m^2]$	-2.24
Balance 2	$[kg/m^2]$	-2.25

Water Content $[kg/m^2]$

	Start	End	Min.	Max.
Total Water Content	10.95	8.71	8.47	18.47

Water Content $[kg/m^3]$

Layer/Material	Start	End	Min.	Max.
*Lime Render (0.02m)	30.00	28.84	18.07	229.21
*Hempcrete (388 kg/m³)	33.00	25.99	25.54	46.93
*Lime Plaster (0.015m)	30.00	22.51	17.05	30.00

Time Integral of fluxes

Heat Flux, left side	$[MJ/m^2]$	-494.15
Heat Flux, right side	$[MJ/m^2]$	-492.69
Moisture Fluxes, left side	$[kg/m^2]$	-0.31
Moisture Fluxes, right side	$[kg/m^2]$	1.93

Hygrothermal Sources

Heat Sources	$[MJ/m^2]$	0.0
Moisture Sources	$[kg/m^2]$	0.0
Unreleased Moisture Sources (due to cut-off)	$[kg/m^2]$	0.0

Table 6: Sensitivity Analysis 1

Status of Calculation

Calculation: Time and Date	2/13/2016 7:51:26 AM
Computing Time	7 min,56 sec.
Begin / End of calculation	10/1/2015 / 10/1/2018
No. of Convergence Failures	16

Check for numerical quality

Integral of fluxes, left side (kl,dl)	$[kg/m^2]$	77.06 -76.33
Integral of fluxes, right side (kr,dr)	$[kg/m^2]$	0.33 2.27
Balance 1	$[kg/m^2]$	-1.86
Balance 2	$[kg/m^2]$	-1.86

Water Content $[kg/m^2]$

	Start	End	Min.	Max.
Total Water Content	9.75	7.9	7.7	17.53

Water Content $[kg/m^3]$

Layer/Material	Start	End	Min.	Max.
*Lime Render (0.02m)	30.00	28.77	17.96	228.70
*Hempcrete (388 kg/m³)	29.00	23.29	22.90	43.95
*Lime Plaster (0.015m)	30.00	22.61	17.20	30.00

Time Integral of fluxes

Heat Flux, left side	$[MJ/m^2]$	-553.58
Heat Flux, right side	$[MJ/m^2]$	-552.25
Moisture Fluxes, left side	$[kg/m^2]$	0.75
Moisture Fluxes, right side	$[kg/m^2]$	2.61

Hygrothermal Sources

Heat Sources	$[MJ/m^2]$	0.0
Moisture Sources	$[kg/m^2]$	0.0
Unreleased Moisture Sources (due to cut-off)	$[kg/m^2]$	0.0

Table 7: Sensitivity Analysis 2

Status of Calculation

Calculation: Time and Date	2/11/2016 10:36:23 PM
Computing Time	7 min,47 sec.
Begin / End of calculation	10/1/2015 / 10/1/2018
No. of Convergence Failures	11

Check for numerical quality

Integral of fluxes, left side (kl,dl)	[kg/m²]	77.98 -77.09
Integral of fluxes, right side (kr,dr)	[kg/m²]	0.3 2.32
Balance 1	[kg/m²]	-1.72
Balance 2	[kg/m²]	-1.72

Water Content [kg/m²]

	Start	End	Min.	Max.
Total Water Content	9.75	8.04	7.84	17.59

Water Content [kg/m³]

Layer/Material	Start	End	Min.	Max.
*Lime Render (0.02m)	30.00	28.96	17.94	228.74
*Hempcrete (388 kg/m³)	29.00	23.74	23.38	44.15
*Lime Plaster (0.015m)	30.00	22.47	16.95	30.00

Time Integral of fluxes

Heat Flux, left side	[MJ/m²]	-444.86
Heat Flux, right side	[MJ/m²]	-443.58
Moisture Fluxes, left side	[kg/m²]	0.91
Moisture Fluxes, right side	[kg/m²]	2.63

Hygrothermal Sources

Heat Sources	[MJ/m²]	0.0
Moisture Sources	[kg/m²]	0.0
Unreleased Moisture Sources (due to cut-off)	[kg/m²]	0.0

Table 8: Sensitivity Analysis 3

Status of Calculation

Calculation: Time and Date	2/12/2016 8:34:33 AM
Computing Time	8 min,37 sec.
Begin / End of calculation	10/1/2015 / 10/1/2018
No. of Convergence Failures	14

Check for numerical quality

Integral of fluxes, left side (kl,dl)	[kg/m²]	79.43 -78.28
Integral of fluxes, right side (kr,dr)	[kg/m²]	0.28 2.37
Balance 1	[kg/m²]	-1.5
Balance 2	[kg/m²]	-1.5

Water Content [kg/m²]

	Start	End	Min.	Max.
Total Water Content	9.75	8.26	8.08	17.67

Water Content [kg/m³]

Layer/Material	Start	End	Min.	Max.
*Lime Render (0.02m)	30.00	29.24	17.90	228.79
*Hempcrete (388 kg/m³)	29.00	24.47	24.16	44.41
*Lime Plaster (0.015m)	30.00	22.31	16.62	30.00

Time Integral of fluxes

Heat Flux, left side	[MJ/m²]	-307.31
Heat Flux, right side	[MJ/m²]	-306.18
Moisture Fluxes, left side	[kg/m²]	1.16
Moisture Fluxes, right side	[kg/m²]	2.65

Hygrothermal Sources

Heat Sources	[MJ/m²]	0.0
Moisture Sources	[kg/m²]	0.0
Unreleased Moisture Sources (due to cut-off)	[kg/m²]	0.0

Table 9: Sensitivity Analysis 4

6. Film Result

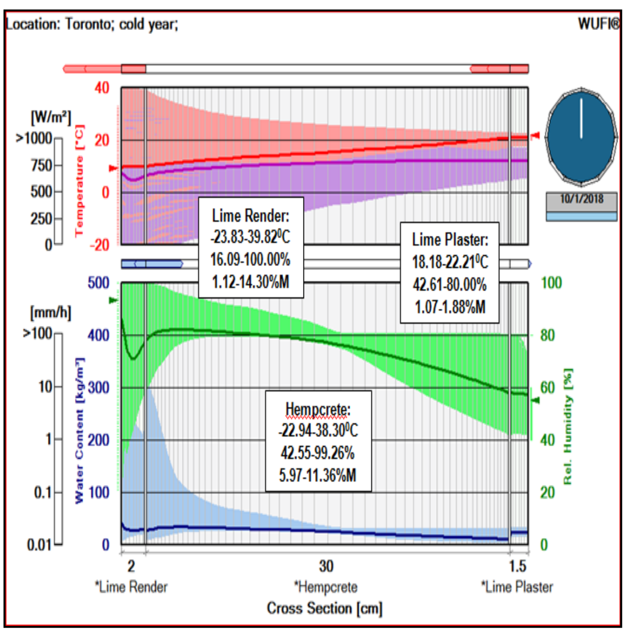


Figure 15: Assembly 1 (Base Case)

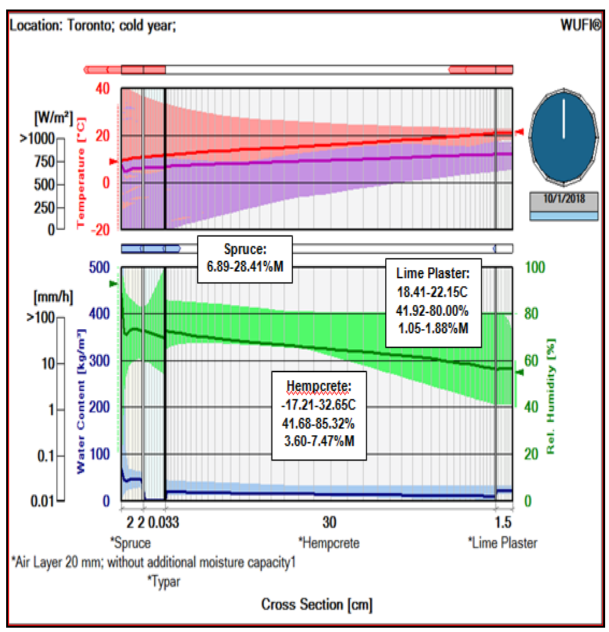


Figure 16: Assembly 2

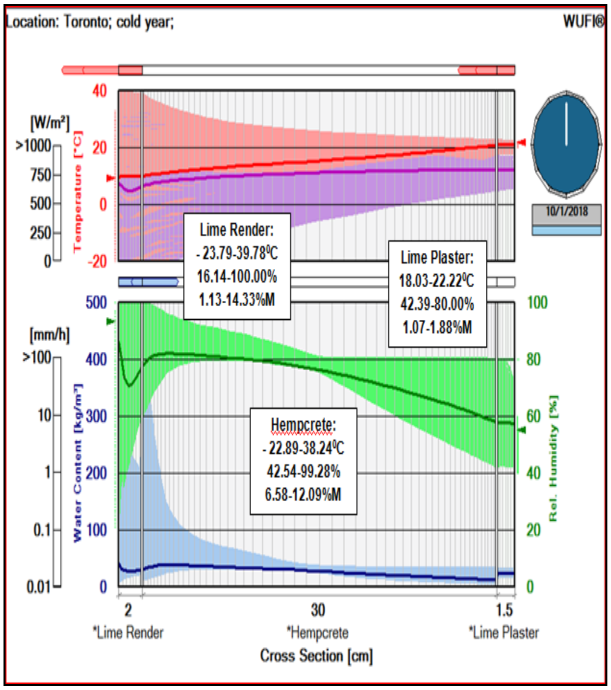


Figure 17: Sensitivity Analysis 1

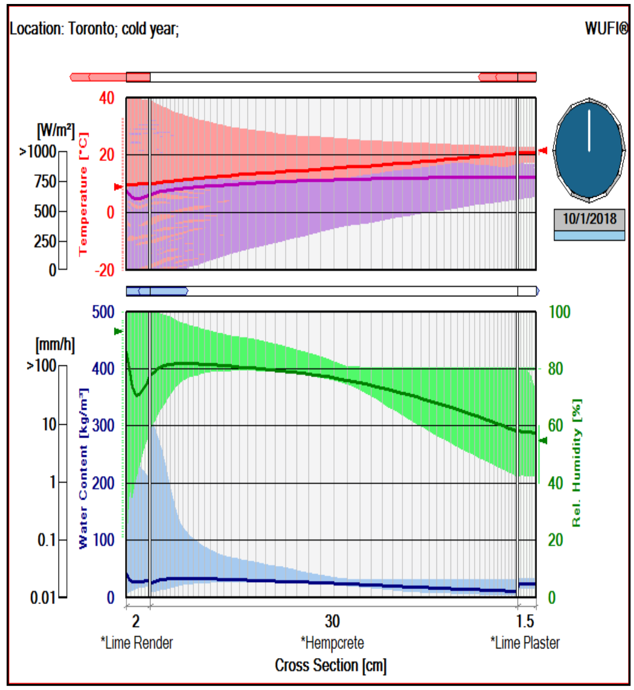


Figure 18: Sensitivity Analysis 2

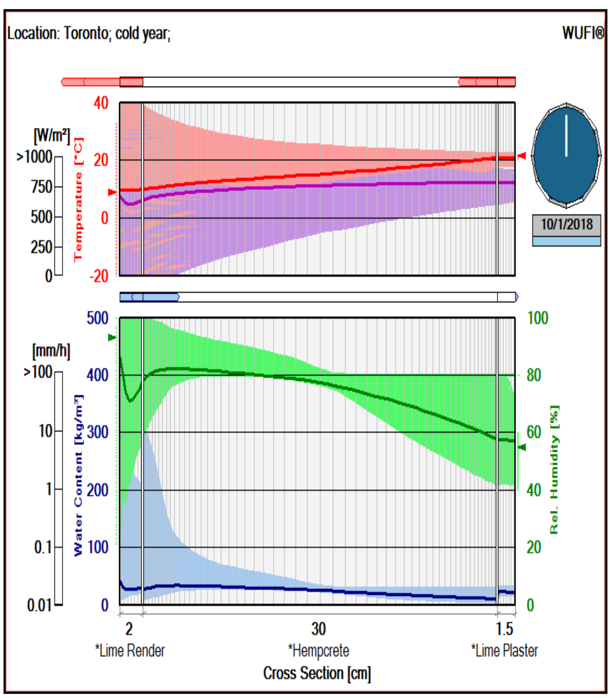


Figure 19: Sensitivity Analysis 3

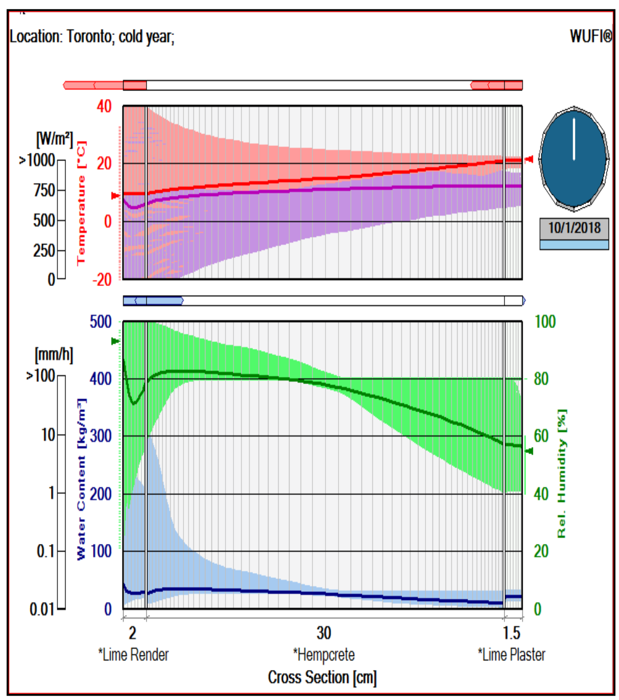
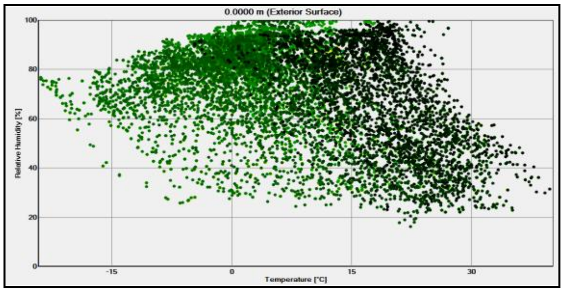


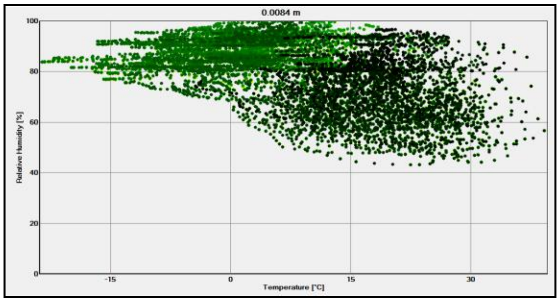
Figure 20: Sensitivity Analysis 4

7. Mold Isopleths Distribution

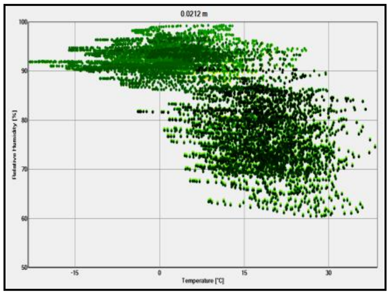
Assembly 1



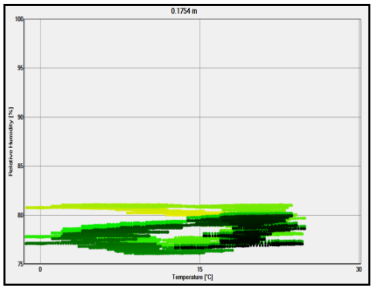
Lime Render- Exterior Surface (M-1)



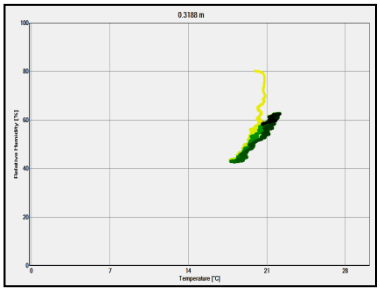
Middle (M-2)



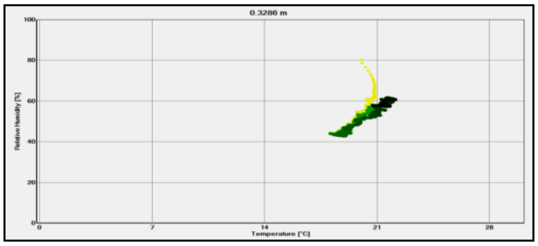
Hempcrete- Exterior (M-3)



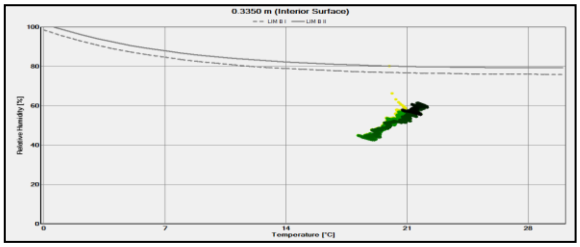
Middle (M-4)



Interior (M-5)



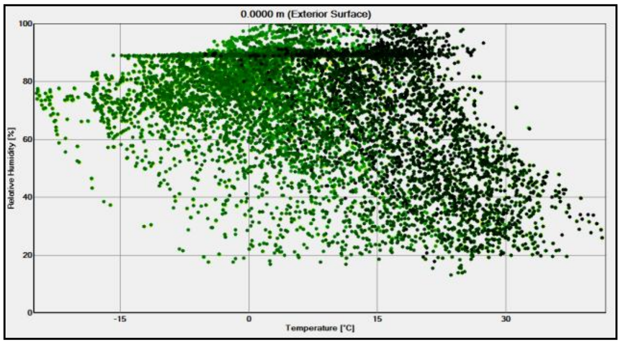
Lime Plaster-   Middle (M-6)



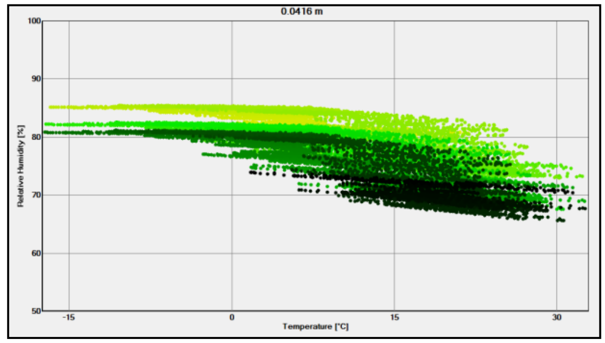
Interior Surface (M-7)

Figure 21: Assembly 1

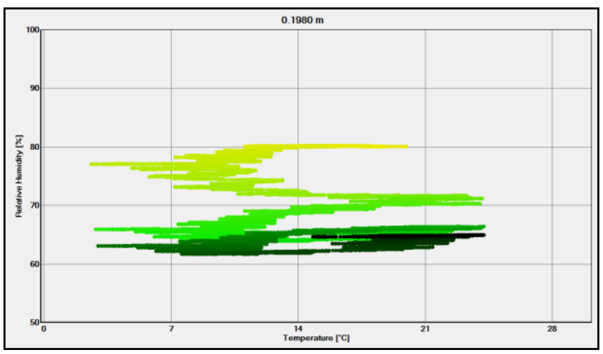
Assembly 2



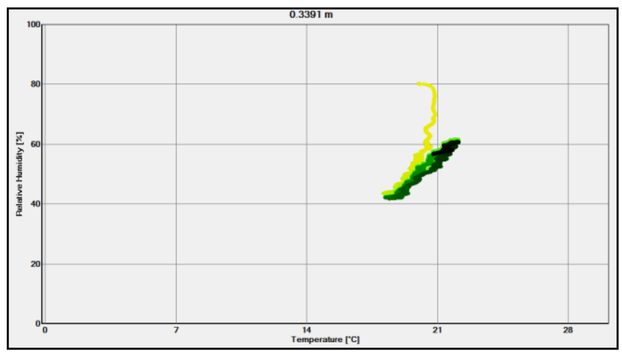
Spruce- Exterior Surface (M-1)



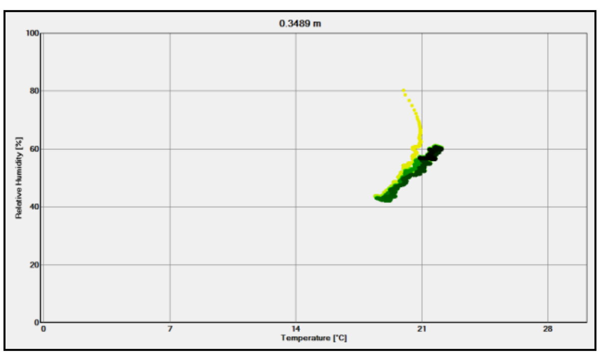
Hempcrete Exterior (M-2)



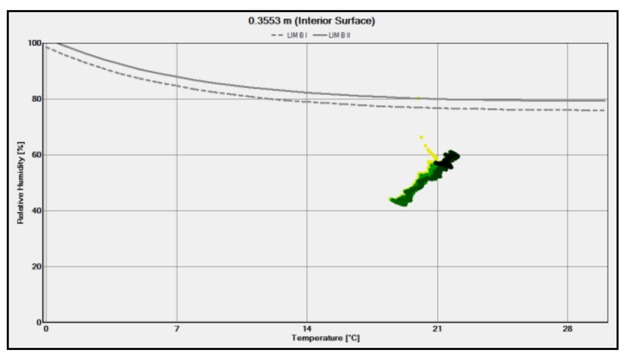
Hempcrete- Middle (M-3)



Interior (M-4)



Lime Plaster- Middle (M-5)

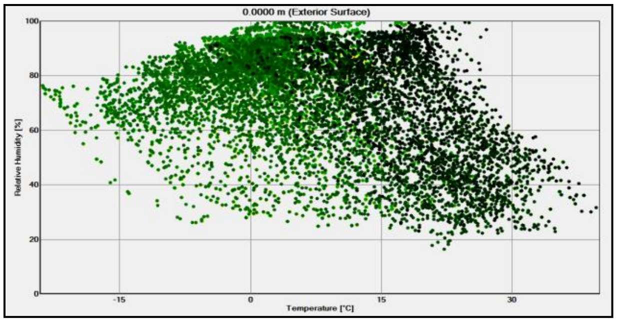


Interior Surface (M-6)

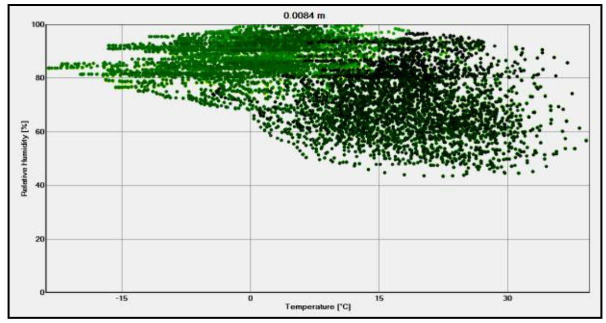
Figure 22: Assembly 2

Sensitivity Analysis

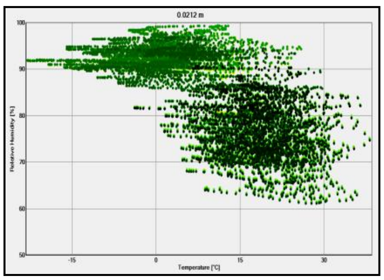
Sensitivity Analysis 1



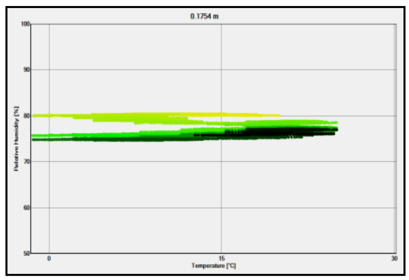
Lime Render- Exterior Surface (M-1)



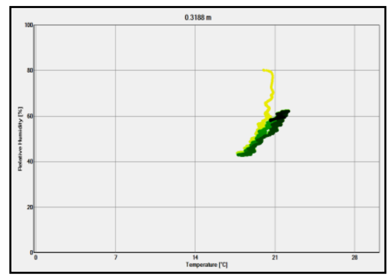
Middle (M-2)



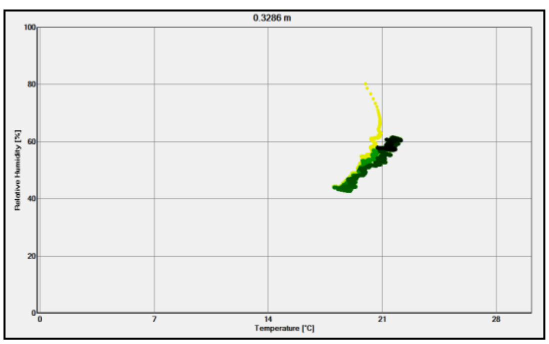
Hempcrete- Exterior (M-3)



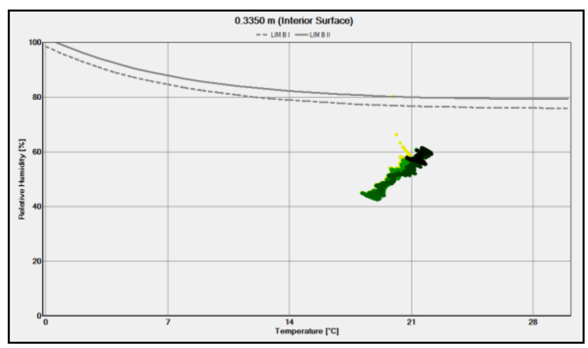
Middle (M-4)



Interior (M-5)



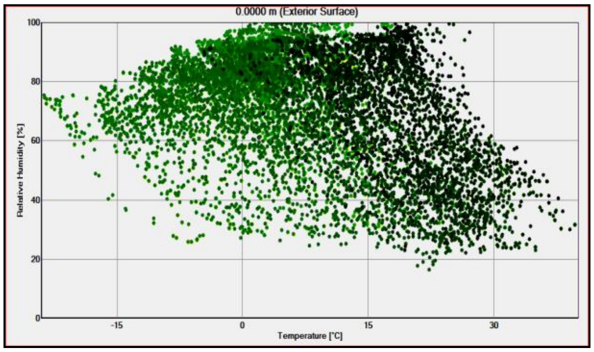
Lime Plaster- Middle (M-6)



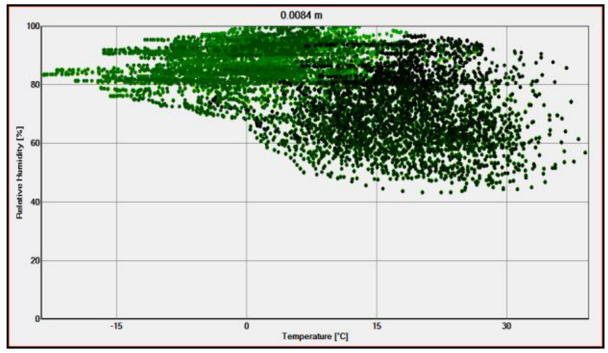
Interior Surface (M-7)

Figure 23: Sensitivity Analysis 1

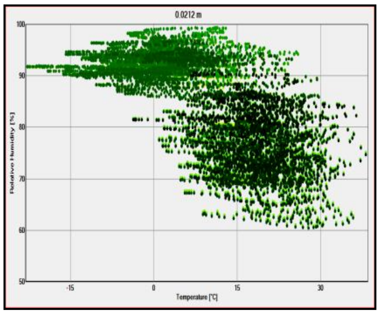
Sensitivity Analysis 2



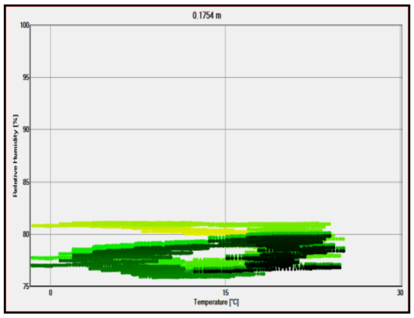
Lime Render- Exterior Surface (M-1)



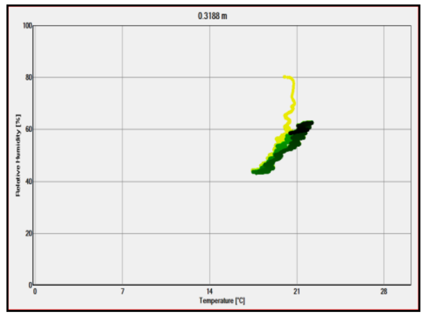
Middle (M-2)



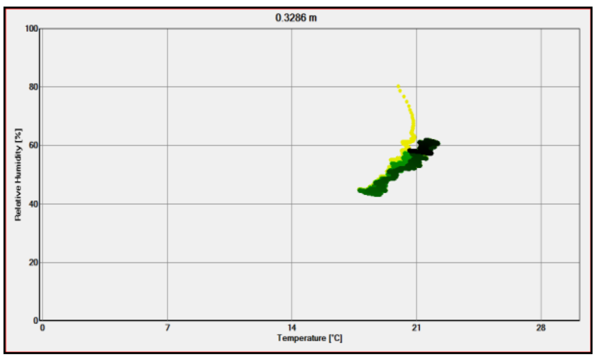
Hempcrete- Exterior (M-3)



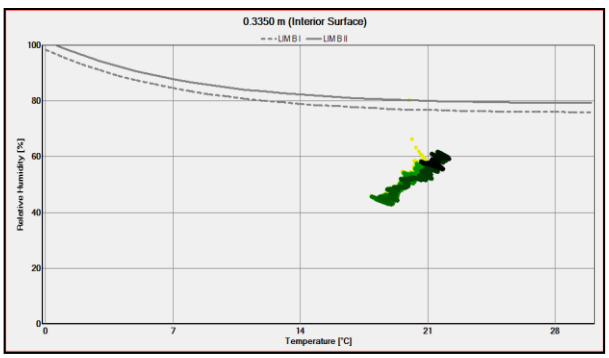
Middle (M-4)



Interior (M-5)



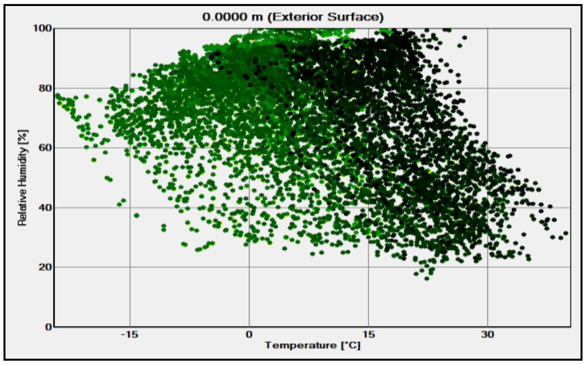
Lime Plaster- Middle (M-6)

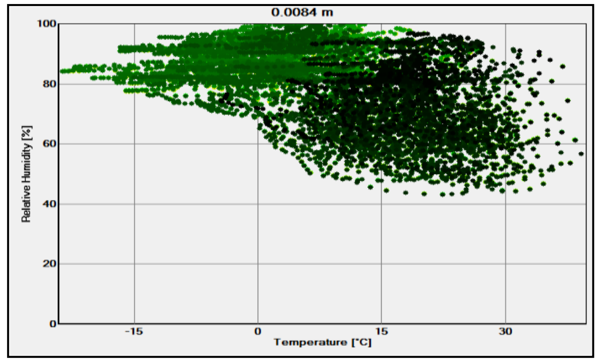


Interior Surface (M-7)

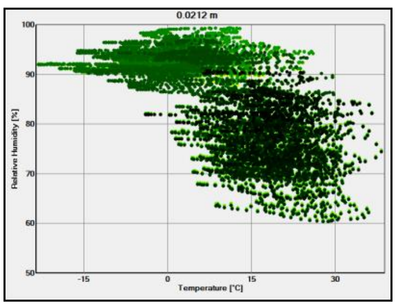
Figure 24: Sensitivity Analysis 2

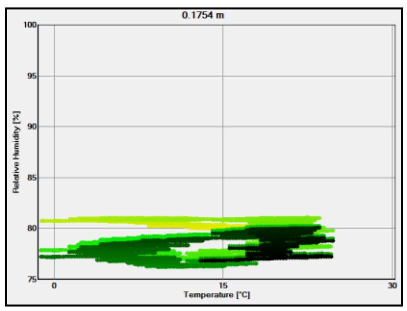
Sensitivity Analysis 3

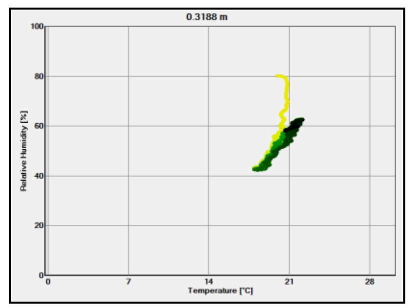




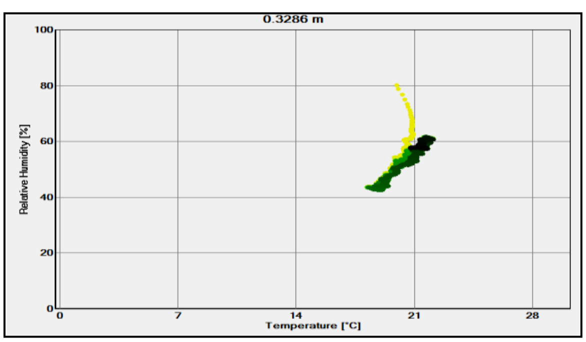
Lime Render- Exterior Surface (M-1)   Middle (M-2)

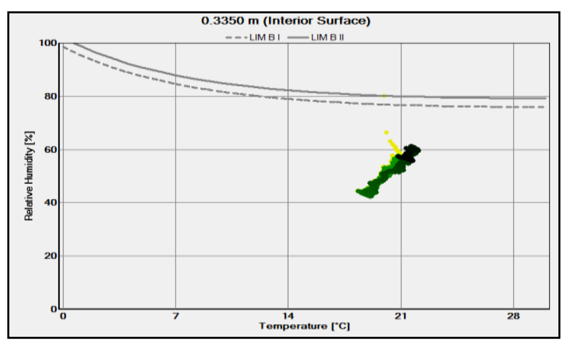






Hempcrete- Exterior (M-3)   Middle (M-4)   Interior (M-5)

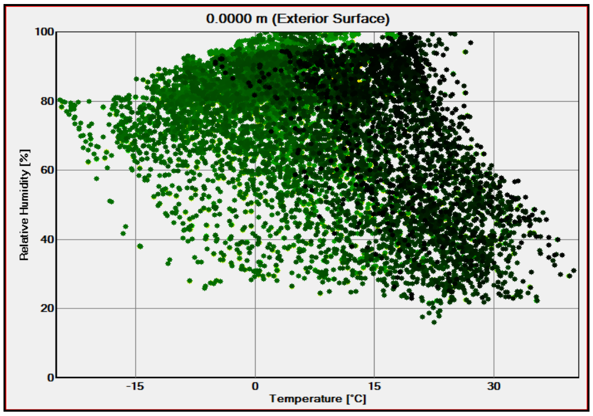


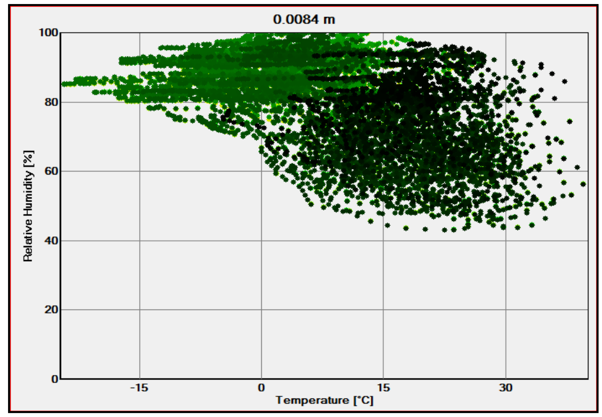


Lime Plaster-   Middle (M-6)   Interior Surface (M-7)

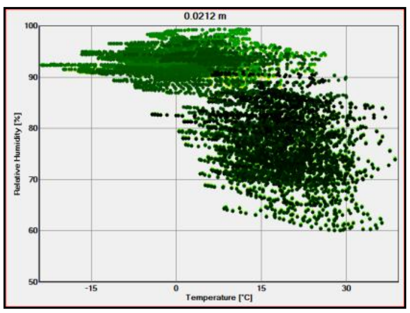
Figure 25: Sensitivity Analysis 3

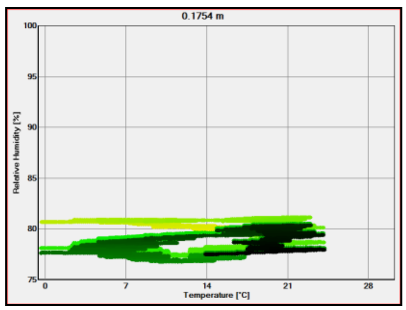
Sensitivity Analysis 4

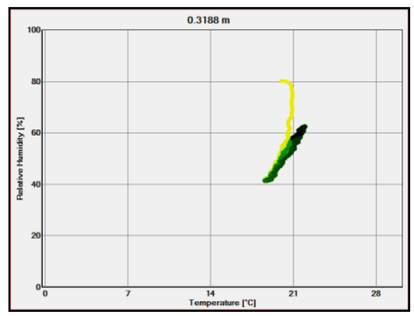




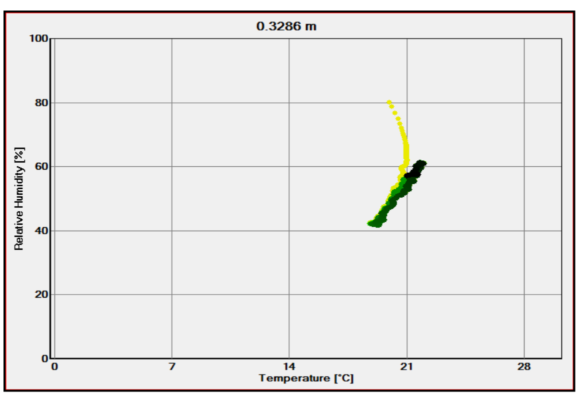
Lime Render- Exterior Surface (M-1) Middle (M-2)

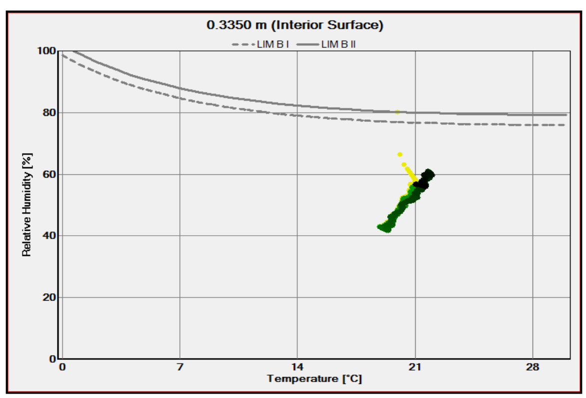






Hempcrete- Exterior (M-3) Middle (M-4) Interior (M-5)





Lime Plaster- Middle (M-6) Interior Surface (M-7)

Figure 26: Sensitivity Analysis 4

8. Water Content

Lime Render and Plaster (Sensitivity Analysis)

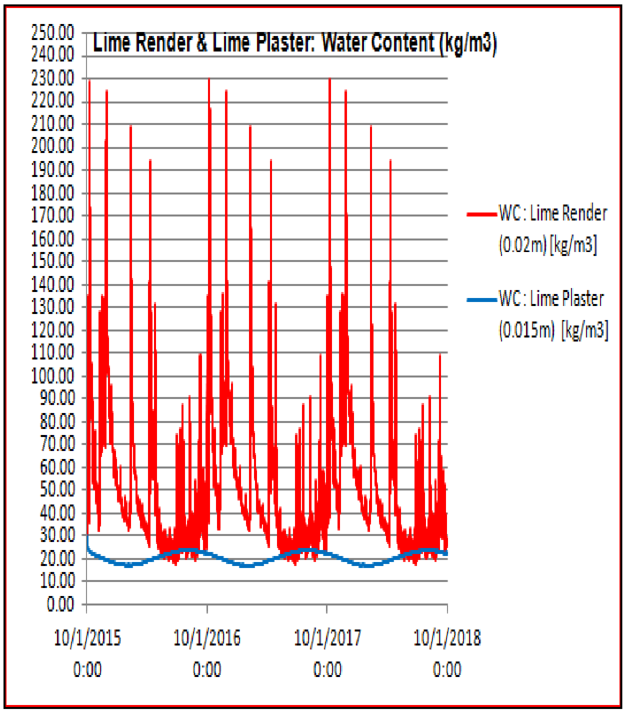


Figure 27: Sensitivity Analysis 1

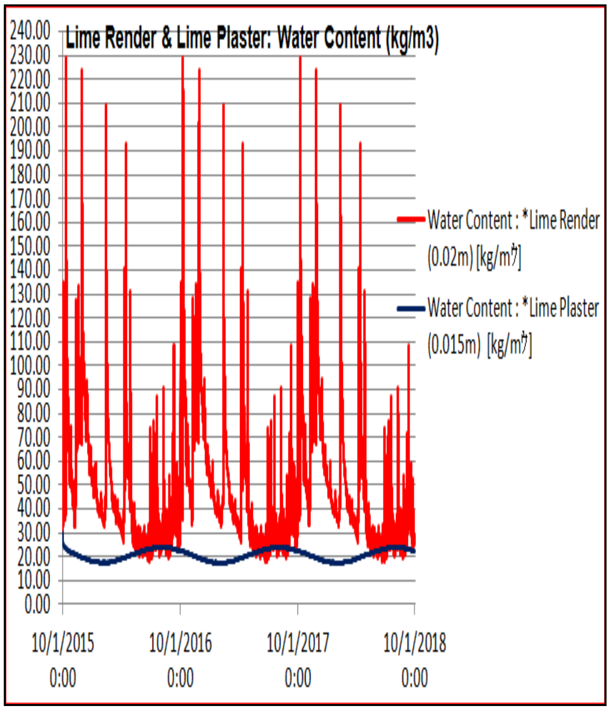


Figure 28: Sensitivity Analysis 2

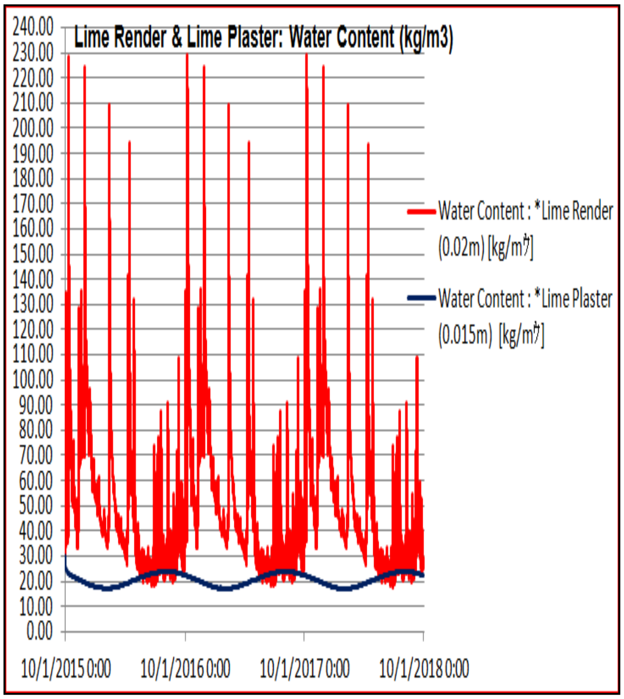


Figure 29: Sensitivity Analysis 3

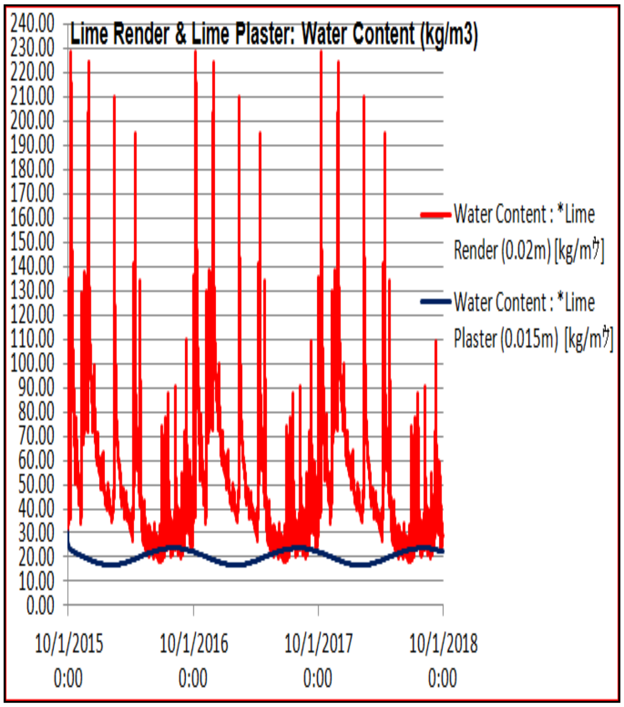


Figure 30: Sensitivity Analysis 4

9. Temperature and RH

Lime Render (Sensitivity Analysis)

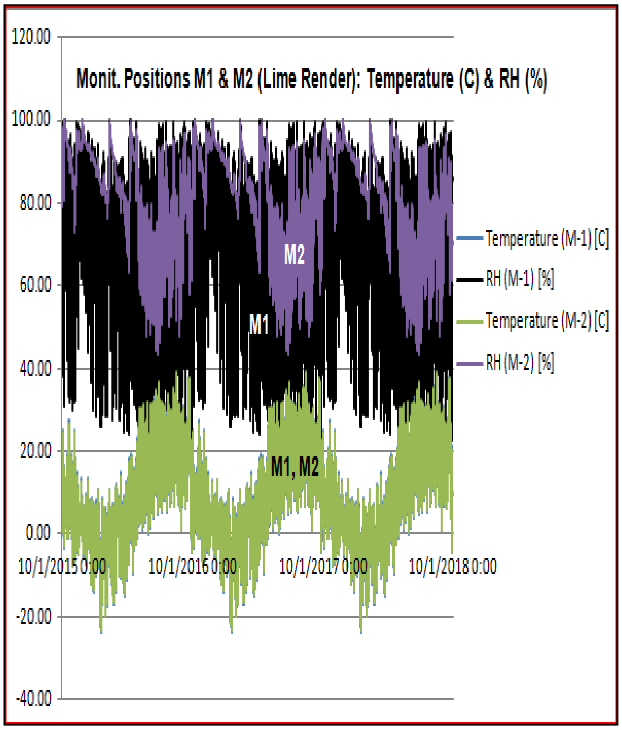


Figure 31: Sensitivity Analysis 1

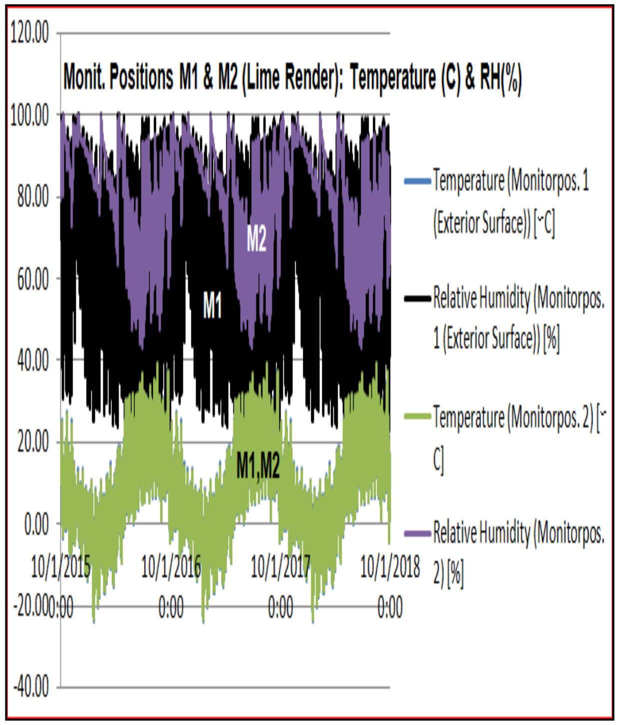


Figure 32: Sensitivity Analysis 2

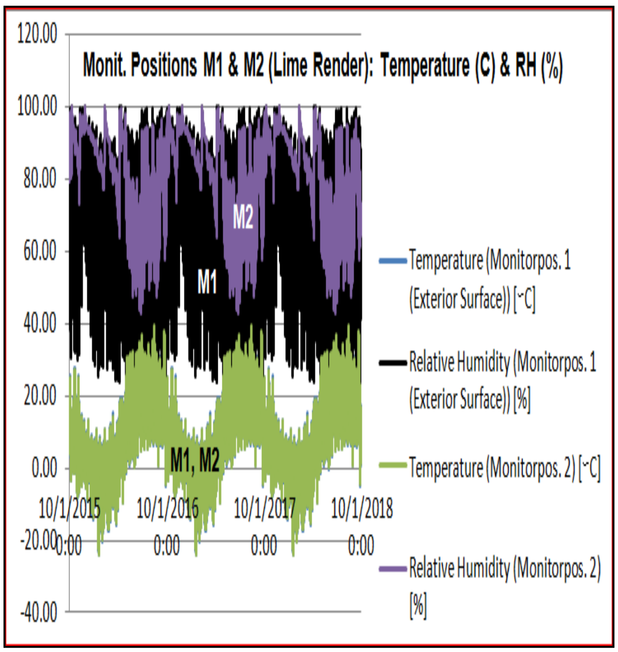


Figure 33: Sensitivity Analysis 3

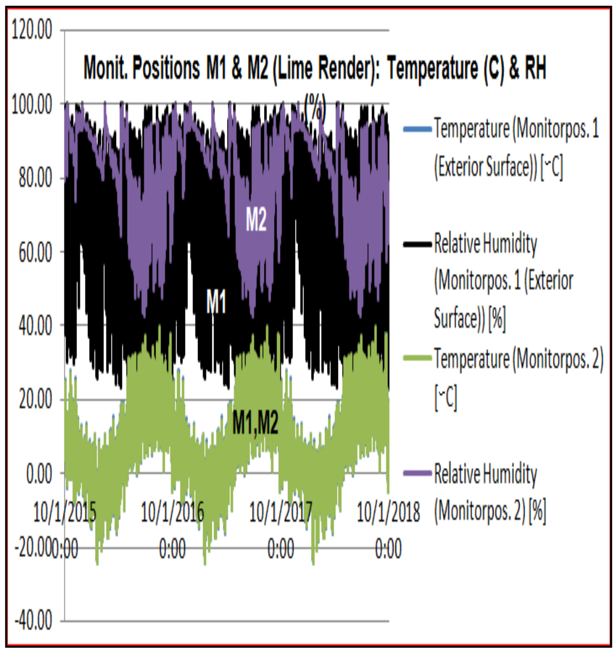


Figure 34: Sensitivity Analysis 4

Lime Plaster (Sensitivity Analysis)

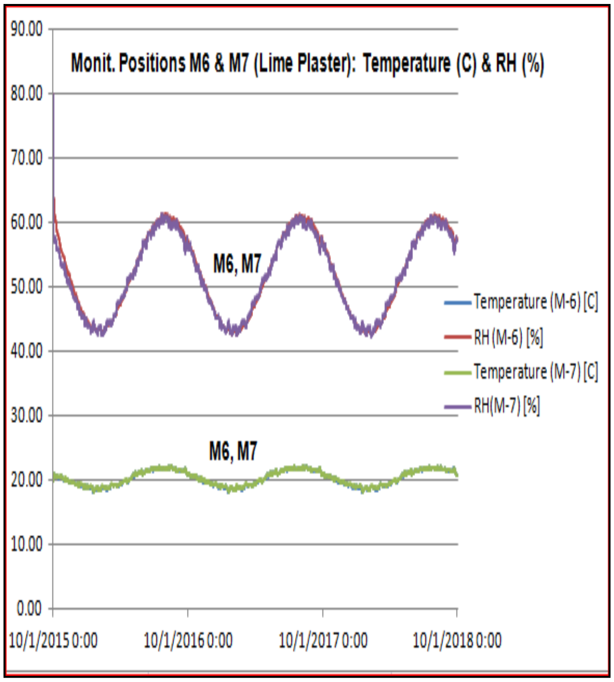


Figure 35: Sensitivity Analysis 1

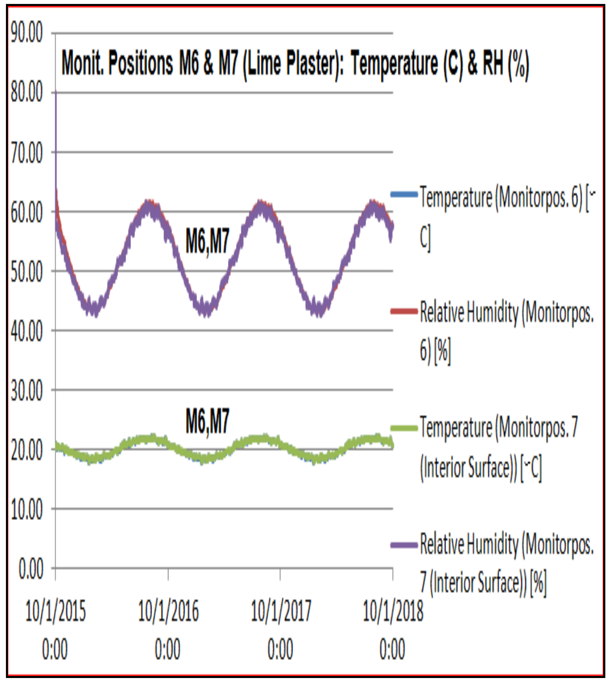


Figure 36: Sensitivity Analysis 2

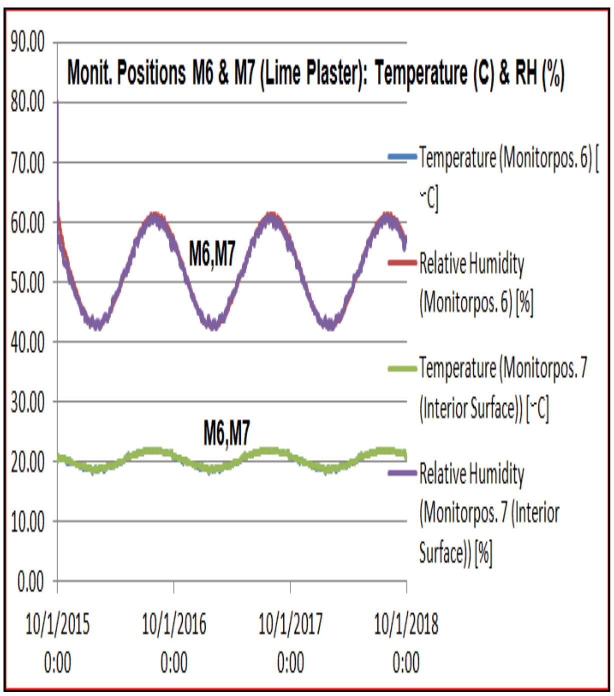


Figure 37: Sensitivity Analysis 3

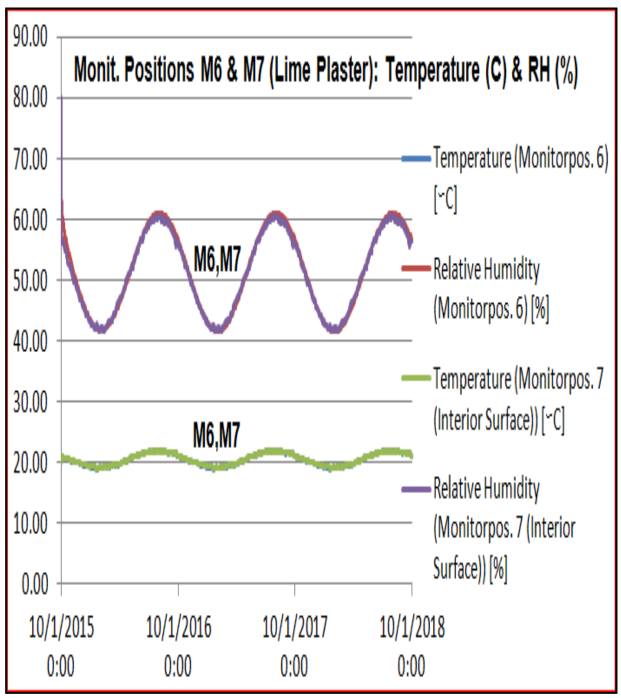


Figure 38: Sensitivity Analysis 4

10. Profiles: Temperature, RH and WC profiles at starting and end of simulation period (Sensitivity Analysis)

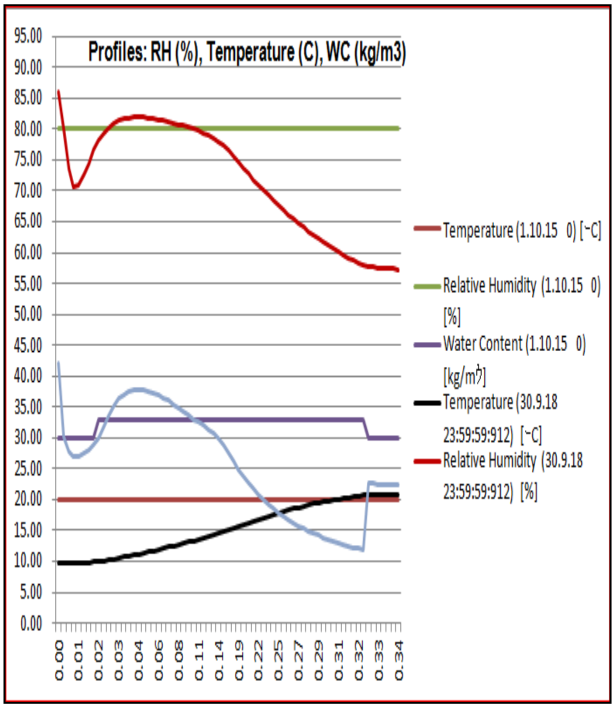


Figure 39: Sensitivity Analysis 1

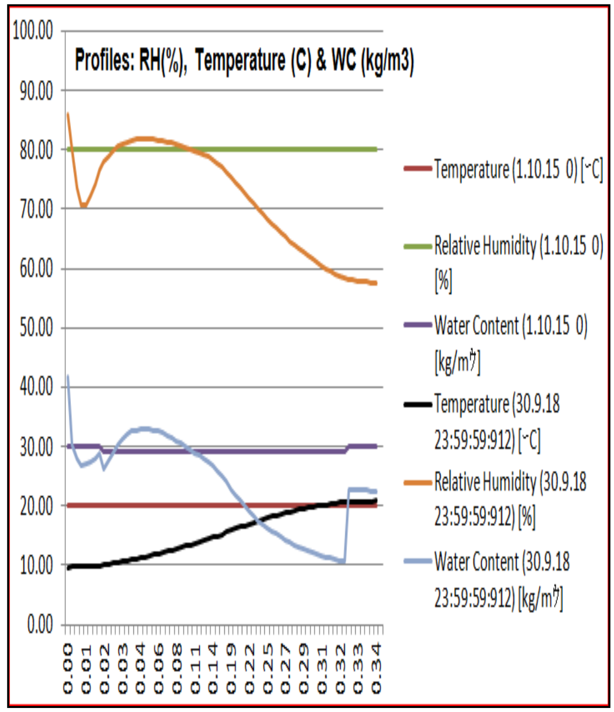


Figure 40: Sensitivity Analysis 2

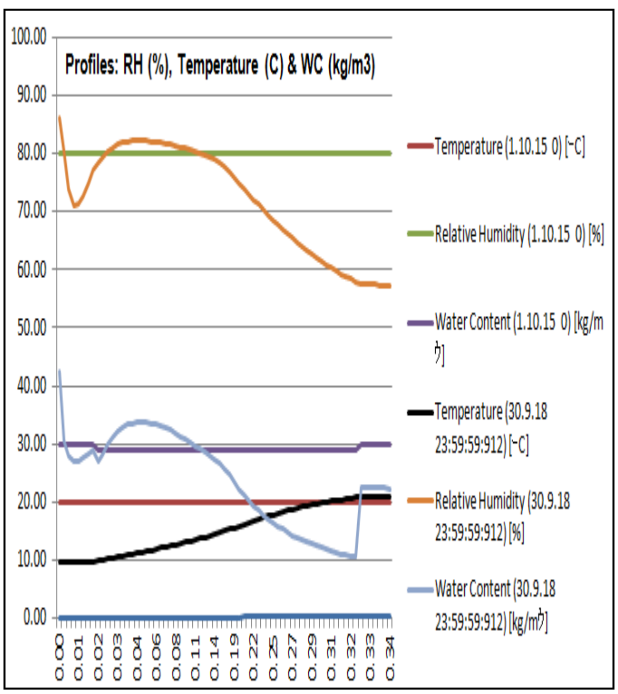


Figure 41: Sensitivity Analysis 3

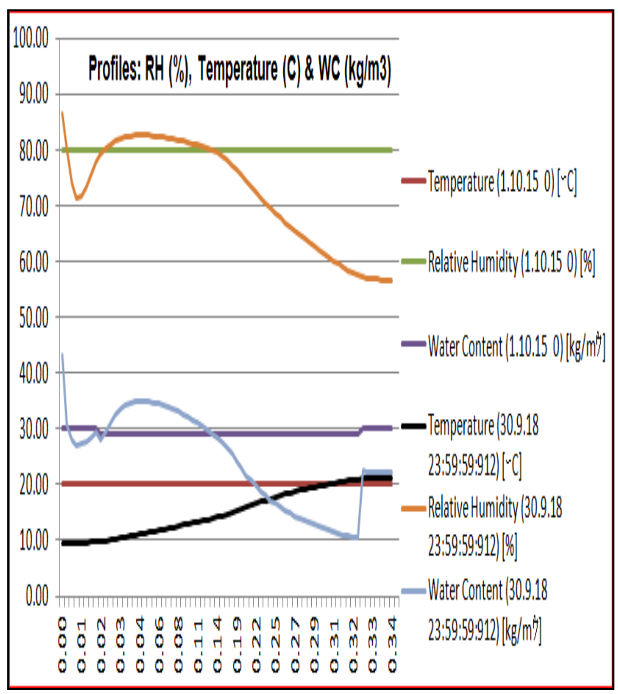
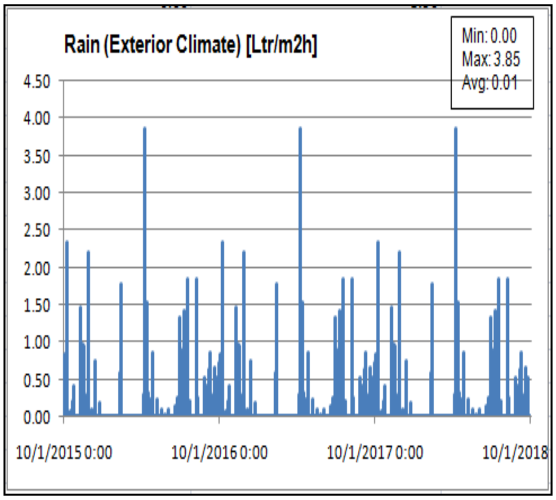


Figure 42: Sensitivity Analysis 4

11. Rain, Solar radiation, Exterior & Interior temperatature and RH



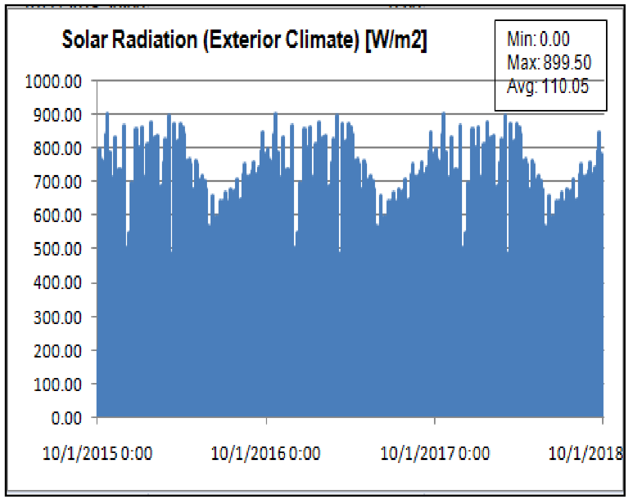


Figure 43: Rain Intensity

Figure 44: Solar Radiation

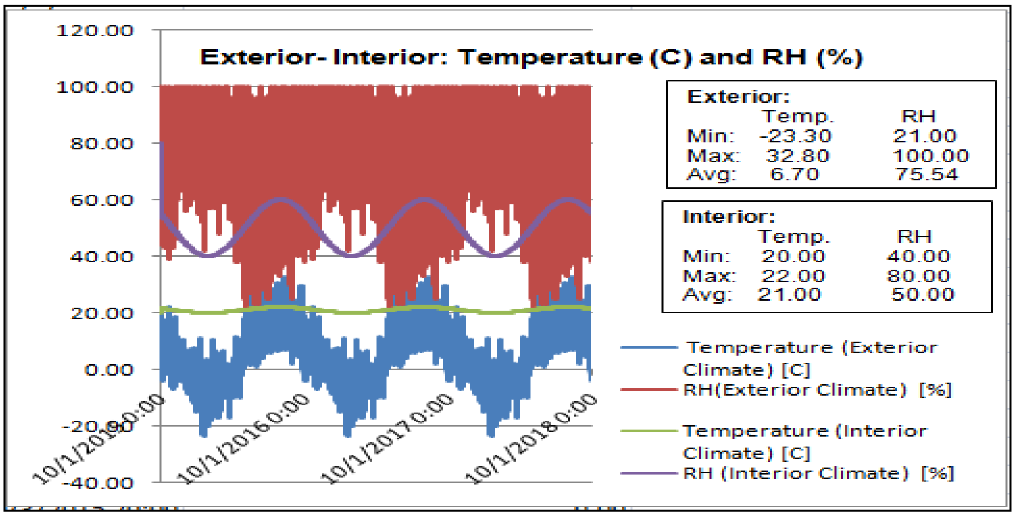
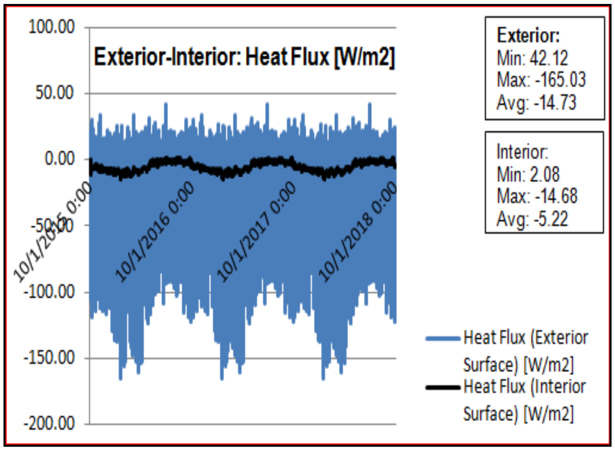


Figure 45: RH and Temperature (Exterior and Interior)

12. Heat flux and Thermal transmission



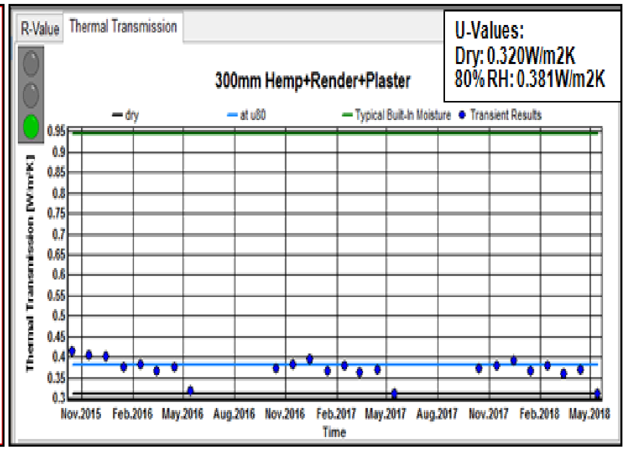
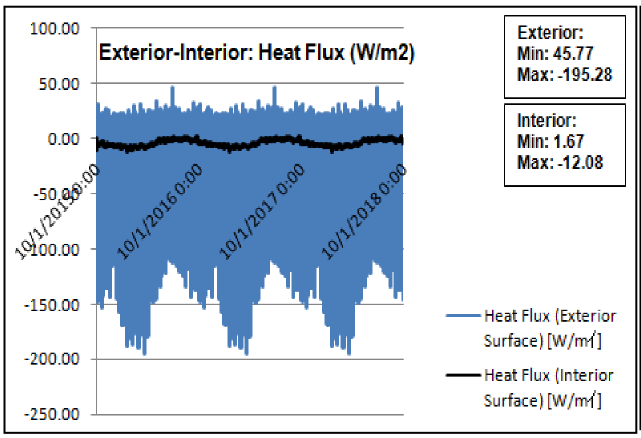


Figure 46: Heat Flux

Figure 47: Thermal Transmission

(Assembly 1, Base Case)



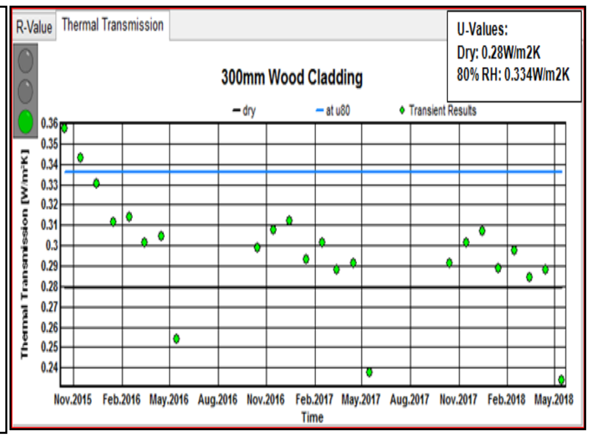
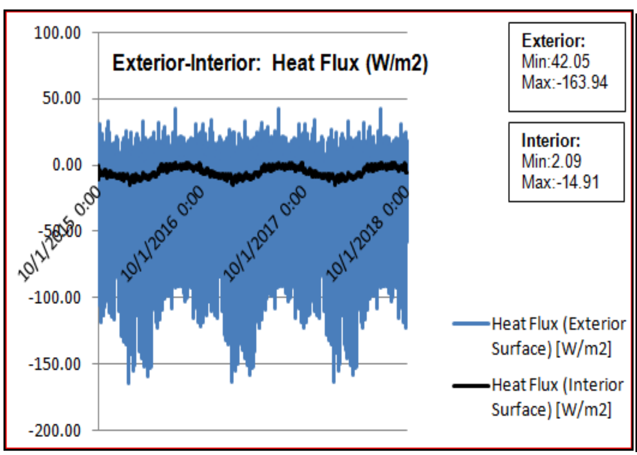


Figure 48: Heat Flux

Figure 49: Thermal Transmission

(Assembly 2)



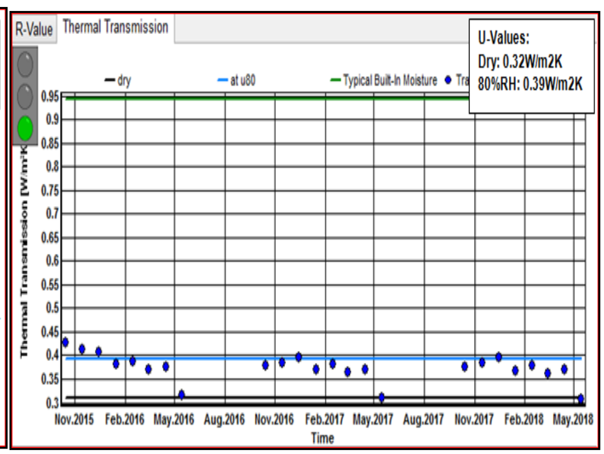


Figure 50: Heat Flux

Figure 51: Thermal Transmission

(Sensitivity Analysis1)

Appendix E: Dry Thermal Conductivity (k) and "R" Value measurements

1. Dry Thermal Conductivity ("k_0")

Thermal conductivity ("k"- W/mK) is a material property that indicates the quantity of heat flow across a unit area through a unit thickness for a temperature gradient of 1^0C (Straube, 2007) or the rate of the passage of heat flow through the material (Evard, 2008). It is calculated by k_0= qd/ ΔT, where q (W/m^2) = Heat flow, ΔT (°C) = Temperature difference between two plates and d (m) = Thickness of the samples.

2. "R" Values

R-value is the resistance to heat flow of a homogenous layer or assembly of materials. According to Fourier's law, R = (ΔT A)/ Q = ΔT/q (lumps all three modes -conduction, convection and radiation into one metric). Subject to all heat flow by conduction, and all materials homogenous and no temperature sensitivities: R = d/k (or 1/U); where, d (m) = Thickness of the samples and k (W/mK) = Thermal conductivity.

Measurements

Dry thermal conductivity (k_0) (W/mK) was measured in accordance with ASTM C518 (Standard Test Method for Steady-State Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus). The equipment used for the test was NETZSCH-HFM 436/3/E with 2 heat flux transducers in series with one specimen (Figures 1-2). 9 dried samples (3 for each mix) of size ≈ 30.5cmx30.5cmx7.62cm were tested in ambient conditions ≈20°C, 50% RH maintaining a temperature difference of 10°C between hot (25^0C) and cold (15^0C) plates (Table 1). Measurements of mean dry thermal conductivity found were 0.074, 0.088 and 0.103 W/mK (± 5%) for mix 1, mix 2 and mix 3 respectively (Table 2 and Table 5). Value obtained for Mix 1 was slightly higher than reference; however, Mix 2 and Mix 3 were within the references. Similarly, R values (Table 2) for the mixes found were between ≈1.5-2.0/inch (1.94, 1.64 and 1.41 per inch for mix 1, mix 2 and mix 3 respectively), little lower than claimed in references (2-2.5/inch).

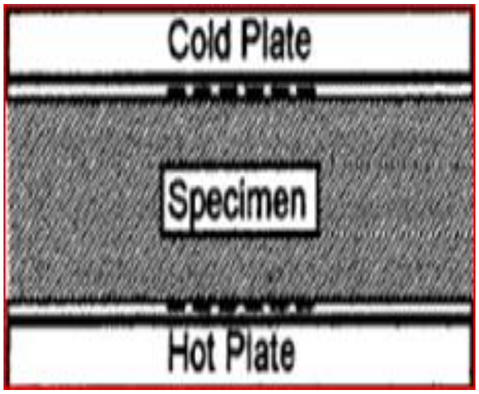


Figure 1: Test Apparatus (ASTM C518)

Figure 2: Test Equipment (NETZSCH-HFM 436/3/E) and test in progress

Plate Temperature		Set points		Offsets	
Hot	Cold	Mean	Delta (T)	Mean	Delta (T)
25^{0}C	15^{0}C	20^{0}C	10^{0}C	0.45^{0}C	0.86^{0}C

Table 1: Test Conditions

Mix & Density	Samples	"k" (W/mK)	"k"- Mean (W/mK) (± 5.00%)	Increment (In reference to mix 1)	"R" /Inch (Imperial) (± 5.00%)	Reduction (In reference to mix 1)
1 (233 kg/m3) (Hemp to Binder 1:1)	1	0.075	**0.074**	**-**	**1.94**	-
	2	0.073				
	3	0.075				
2 (317 kg/m3) (Hemp to Binder 1:1.5)	1	0.088	**0.088**	18.39%	**1.64**	-15.53%
	2	0.088				
	3	0.088				
3 (388 kg/m3) (Hemp to Binder 1:2)	1	0.104	**0.103**	38.12%	**1.41**	-27.60%
	2	0.106				
	3	0.098				

Table 2: Dry Thermal Conductivity (k) & R Values

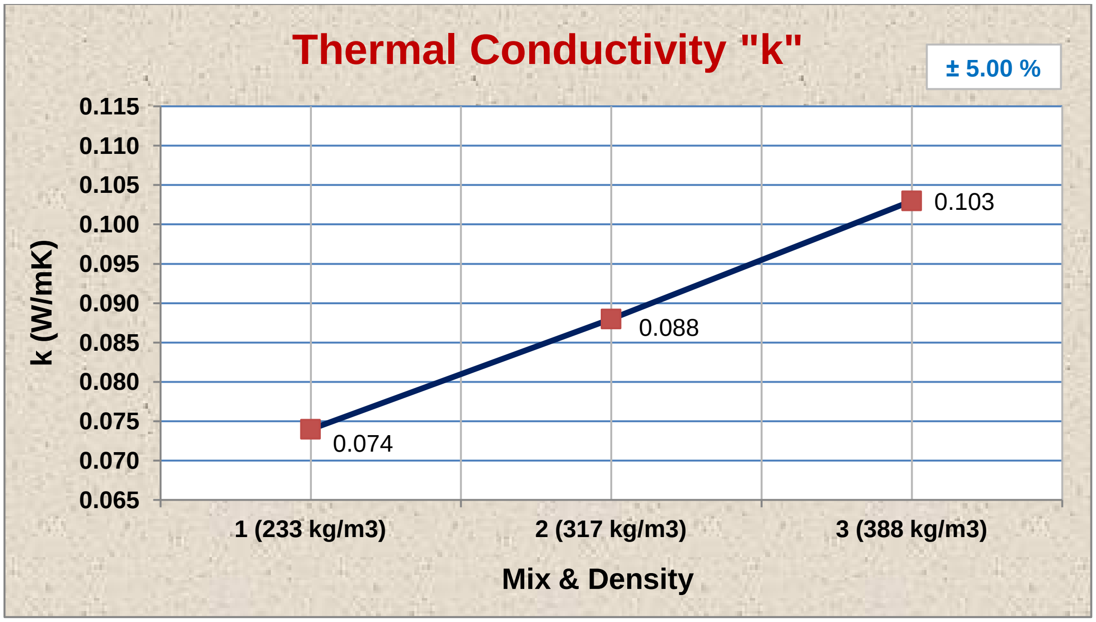


Figure 3: Dry Thermal Conductivity vs Densities

Based on the above graph (Figure 3), it can be concluded that the dry thermal conductivity of hempcrete maintains almost a linear relationship with density; when density increases, “k” increases, vice versa.

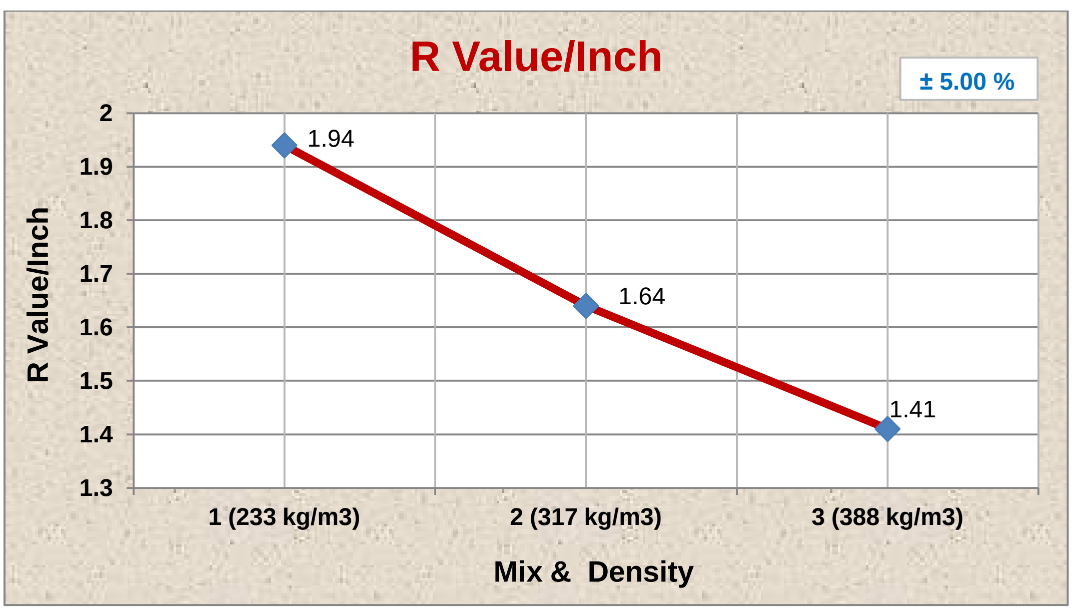


Figure 4: R Values vs Densities

As shown in the above graph (Figure 4), density and R value has inverse relationship; when density increases, R value decreases, vise versa.

Table 5: Test results produced by the machine