A METHOD FOR DETERMINING THE RELATIONSHIP BETWEEN INCREASING INSULATION AND POTENTIAL FREEZE THAW DAMAGE IN BRICK MASONRY WALLS

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Abstract

A Method for Determining the Relationship between Increasing Insulation and Potential Freeze Thaw Damage in Brick Masonry Walls

By Braden Johnson

Master of Building Science in the Program of Building Science 2016

When considering insulation retrofits, property limit distances and setbacks make interior insulation of residential homes the only viable option. When pursuing an interior insulation retrofit the potential for brick masonry freeze thaw damage needs to be considered. Studying the impacts of an interior insulation retrofit Pre-World War 2 residential building in Toronto, Ontario, a comparison of the retrofitted building using WUFI against 8 other insulation types was completed to determine if the change of insulation affects the potential for freeze thaw damage. Based on the results of the WUFI analysis the answer would be yes. The insulation type and R value does have an impact brick masonry freeze thaw resistance. However this relationship is general and not linear. The method provided shows that if critical saturation (S_{CRIT}) is known predictive modeling on the impacts of interior insulation on the moisture performance of the brick masonry wall can be used.

Acknowledgements

Thanks to Ryerson University and the hard working Faculty of Architecture Science Professor Russell Richman and Professor Hitesh Doshi for your time, energy and insight. Thanks to the previous researchers who contributed to the body of knowledge that this work follows in the footsteps of. I have done my best to acknowledge all of your significant contributions that informed this project. Most important I would like to thank my family for their support and the universal creative force that pushes us all to learn more.

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Glossary

- [a] *Freeze thaw damage* – Permanent irreversible expansion of brick masonry measured in microstrain that occurs during a 0 degree crossing from thaw to freeze. Also known as frost damage.

- [b] *Critical Saturation (S_{CRIT})* – The ratio of maximum water that can be held in the material *(S_{MAX})* to the amount of water held in the material when it is in a saturated state and freeze thaw damage occurs.

- [C] *Maximum Water Content (S_{MAX})* – The maximum amount of water content that can be taken up by a material where there are no air pockets remaining. This state can be achieved in the laboratory via vacuum saturation or boiling saturation testing.

- [d] *Freeze Thaw Resistance* – The difference between critical saturation and actual saturation measured at specific point in time.

$$[F = S_{CRIT} – S_{ACT}]$$

- [e] *Degree of Saturation* –The ratio of water held in the material to the amount of water held in the material when it is in a saturated state.

$$[\text{Degree of saturation} = M_{wet} – M_{dry} / M_{MAX} – M_{dry}]$$

- [f] *Frost dilation* – Expansion of brick masonry pore measured in microstrain.

- [g] *Frost dilatometry testing* – A method of brick masonry testing that is used to determine the critical degree of saturation where dilation of a saturated pore occurs beyond the pores ability to maintain its original physical characteristic resulting in permanent damage.

- *Microstrain* – unit of measurement used in frost dilatometry analysis. 1 Microstrain is equal to 0.0001 mm. Based on previous studies expansion of brick masonry pore space greater than 100 Microstrain or 0.01 mm is indicative of frost damage.

- *Hygroscopic* - The ability of a substance to attract and hold water molecules from the surrounding environment. This is achieved through either absorption or adsorption.

- *Moisture Content (MC)* – The ratio of mass of water held in a material to the dry mass of the material.

$$[MC = M_{wet} – M_{dry} / M_{dry} \times 100\%]\ [a]$$

- *Saturated Moisture Content (D_{SAT})* - Moisture content of a material when the entire pore space is filled with liquid.

$$[MC = M_{sat} – M_{dry} / M_{dry} \times 100\%]\ [2]$$

- *Water absorption coefficient (D_{WS})* - also known as absorption rate describes the capillary uptake of water when the imbibing surface is fully wetted.

$$[D_{WS} = kg/m2/s\text{^}0.5]\ [3]$$

- *Free Water Saturation (W_F)* – A capillary active material in contact with water will take up this water until it reaches its free saturation. The water content corresponds to the moisture storage function at a relative humidity of 100%, however there are still air pockets trapped in the pore structure. This value can also be approximated by multiplying the material porosity by the bulk density of water (1000 kg/m^3)

- *Reference Water Saturation (W_{REF})* - the sorption moisture corresponding to 0.8 RH, w80. This value is used as a reference point in WUFI for generating a moisture storage curve.

- *Bulk Density (Kg/m^3)* – is the ratio of the mass of the sample and the total volume of the sample. This data affects the material specific heat value and moisture dependent thermal conductivity results.

- *Porosity (m^3/m^3)* – determines the maximum water content (W_{MAX}) or super saturated state of a material. The value can be estimated by the following [1 – bulk density / true density]. True density is the density of the sample material excluding the volume of open and closed pores.

- *Moisture storage function* – the moisture storage function is described in WUFI by a table with relative humidities (0 – 100% RH) and the corresponding moisture contents. The data collected from previous gravimetric and EMS tests described in Method 4 can be used to approximate this information. WUFI interpolates the data linearly to complete the moisture storage function.

- *Reference water saturation (kg/m3)* – Determined during lab testing of brick masonry sample and used as a reference point in WUFI (WREF). The water content corresponds to the moisture storage function at a relative humidity of 80%.

- *Liquid transport coefficient for suction (m2/s)* – also known as absorption rate describes the capillary uptake of water when the imbibing surface is fully wetted. In the field this is the rate at which moisture is absorbed when rain falls on a brick masonry wall.

- *Super Saturation* – A state where all of the pores and capillaries of a hygroscopic material (brick masonry) are filled with water.

  [S_{sat}]

- *Capillary Saturation* – A state where all of the capillaries of a hygroscopic material (brick masonry) are filled with water.

  [S_{cap}]

- *Critical Moisture Content* – A state where moisture is being held by capillaries at close to 100% relative humidity.

  [S_{crit}]

- *Completely dry* – Mass of material at which moisture content and relative humidity are equal to 0%.

- *Moisture Storage (Function)* - In a porous material, the surfaces of the pore system accumulate water molecules until a specific equilibrium moisture content is reached corresponding to the humidity of the ambient air. At relative humidity points 0 to 100% a moisture storage curve or function is produced.

  [MC / RH] [6]

- *Critical Saturation Resistance* – (Scrit - Sact) as a % of Scrit.

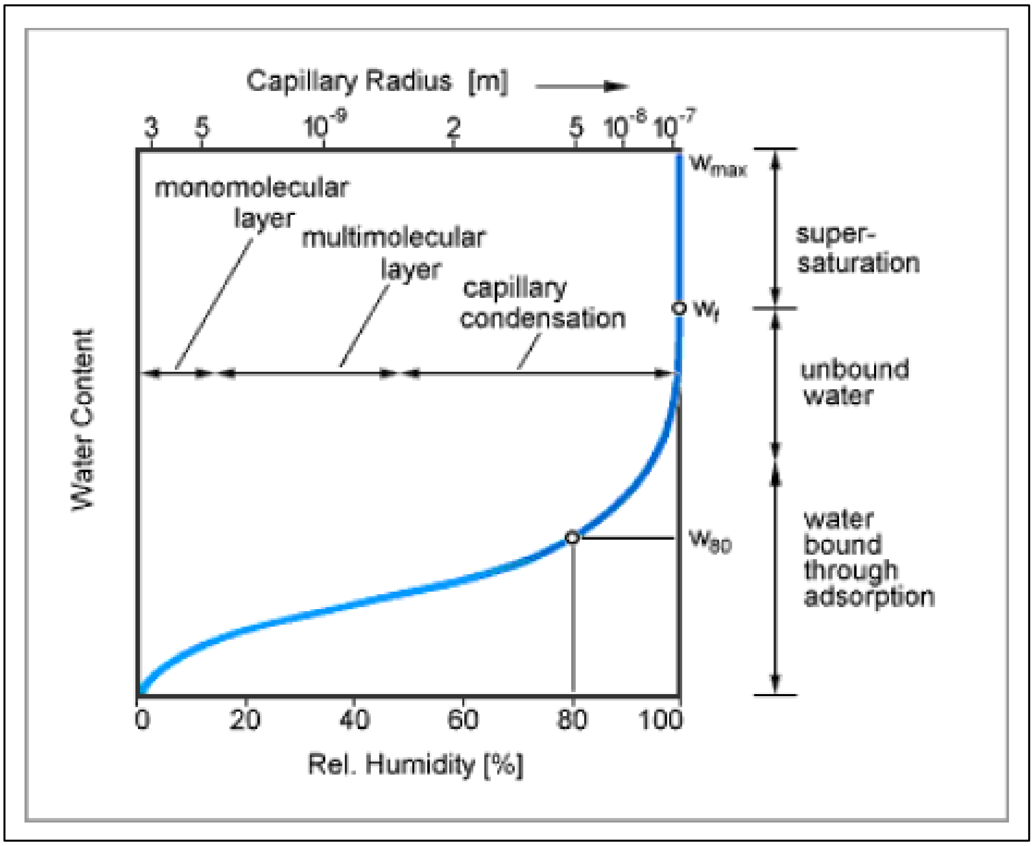


Figure 1 - Moisture Storage Function WUFI PRO

1. Introduction

The issues of climate change, energy security, and economics are all strong drivers for improving energy efficiency levels in a variety of sectors. In residential construction, although some inroads have been made in new houses, the stock of existing brick masonry housing represents a huge opportunity for energy retrofits.

Part of any major building energy retrofit includes adding insulation. Increased insulation decreases the amount of energy required by mechanical systems to heat and cool the building interior. When considering insulation retrofits of existing residential homes, property limit distances and setbacks, particularly in the Toronto area, make interior insulation the only viable option.

While there are several studies which detail preferred methods of completing an interior insulation retrofit, there is a lack of analysis completed on the potential increase to freeze thaw damage of the existing brick masonry wall caused by adding interior insulation. The increased risk is caused by the thermal moisture performance change to the brick masonry structure caused by the installation of interior insulation. The brick masonry wall will experience colder temperatures for longer periods of time during the heating season. The insulation may also affect the interior drying potential of the brick masonry. The combined affect can result in a colder wetter brick masonry structure with an increased potential of brick masonry freeze thaw damage. When making the decision to pursue an interior insulation retrofit method these factors need to be thoroughly considered.

The research paper sets out to determine, for a particular single family brick masonry detached home where the brick critical degree of saturation has been calculated, the relationship between interior insulation values and brick masonry wall potential freeze thaw damage. The analysis tool used for the study was Hygrothermal building simulation software tool WUFI PRO. The completed analysis is proposed as a method that can be used for future interior insulation retrofit case study applications where the relationship between interior insulation and brick masonry freeze thaw damage needs to be ascertained. The subject property studied is a pre-world war 2 brick masonry residential building located in Toronto, Canada.

1.1. Objective

This research paper furthers the knowledgebase of determining the relationship between interior insulation values and brick masonry wall potential freeze thaw damage, using a case study single family brick masonry detached home where the clay brick masonry wall critical degree of saturation has been estimated. Based on the above objective, the following research questions were developed:

1. Given a known estimated critical saturation point for a pre-world war 2 brick type, does the increase or decrease of interior installed insulation type affect the potential for freeze thaw damage that may occur in the

brick masonry structure?

2. Using thermal resistance and potential for freeze thaw as constraints, what is the optimal level of interior insulation for the particular case study?

1.2. Scope

The scope of this research was to demonstrate a method that can be used to evaluate the impacts an interior insulation retrofit will have on a brick masonry building before construction and use this information to specify insulation levels and type without jeopardizing a clay brick masonry walls ability to resist freeze thaw damage brought on by the change in its thermal / moisture performance after the retrofit.

1.3. Approach

A literature review was completed on current research and case studies of interior insulation retrofits and their energy saving potential. The literature review also highlights the potential risks involved in changing the thermal moisture performance of a brick masonry building by adding interior insulation. Using previous research findings, a summary on how to determine the critical saturation of a porous material via frost dilatometry testing is provided along with a brief discussion of how this compares with current resistance to freeze thaw damage ASTM and CSA testing standards. The discussion then proceeds to highlight the challenges involved with using frost dilatometry testing and resolving differences between field and laboratory findings. The use of hygrothermal modeling software programs such as WUFI is introduced as a means to conduct predictive performance modeling of a brick masonry wall if critical saturation data is known. An exercise in modeling 8 different insulation types was completed using literature recommended interior insulation retrofit strategies. The focus of the exercise was the impact to the moisture performance of the brick masonry structure caused by adding the insulation to the interior cavity of the brick masonry structure. Analysis of the results on how the scenarios compare to each other and the original baseline condition is presented followed with a recommendation on which option would likely produce the most optimal results based on the improvement to insulation and resistance to freeze thaw damage. The key elements of the methodology to the MRP can be summarized by the following:

1. Creation of a calibrated baseline model in WUFI that accurately reflects the 2013 actual meteorological year (AMY) data for Toronto.
2. Using the brick masonry critical degree of saturation established from previous research, the baseline WUFI model was run comparing 8 other insulation options recommended from the literature review.
3. The data generated from the WUFI models were converted into excel tables for quantifying the number of freeze thaw cycles and corresponding moisture contents for each proposed insulation retrofit

option.

4. The results were analyzed to determine what, if any, relationship existed between the change in insulation construction and the walls frequency of freeze thaw occurrences where critical saturation has been or was close to being reached.

2. Background

Reducing energy consumption in buildings is becoming a defining problem as it relates to building sustainability and minimizing environmental damage caused by an ever increasing energy demand being placed on diminishing energy resources. The issues of climate change, energy security, and economics are all strong drivers for improving energy efficiency levels in a variety of sectors. In residential construction, some inroads have been made in new houses, however the stock of existing brick masonry housing represents a huge opportunity for energy retrofits [1]. These opportunities exist particularly with the large stock of Toronto pre-World War II load bearing brick masonry homes. The load bearing masonry buildings have potential for long term durability – it is for this reason that many still exist and are available for renovation and conversion after which service lives are well over 50 years [2].

Several studies and guidelines have looked at what combination of building materials work best for a brick masonry wall interior insulation retrofit. One of the strategies include filling an existing stud wall with batt insulation while leaving a ½” to 2” air gap between the studs and the masonry wall. The drywall finish acts as the air barrier and either paint, Kraft facings, polyethylene sheet, or aluminum backing acts as a vapor control layer. The likelihood of condensation and mold growth in the wall with batt insulation and drywall air barrier with vapour control layer however is high. As temperatures drop during winter months warm moist air can flow into the cavity between the masonry and stud wall and will tend to condensate on the cooler (below dew point temperature) interior brick masonry. This solution creates additional design challenges when it comes to regulating the building's interior relative humidity [3].

Semple and Goncalves (2007) [4] demonstrated through simple one dimensional hygrothermal computer modeling, the theoretical concerns relating to increasing the thermal resistance of existing exterior solid masonry walls by analyzing and comparing the differences in the hygrothermal conditions of an uninsulated masonry wall, an interior insulated masonry wall, and an exterior insulated masonry wall under a steady-state winter design conditions for Montréal. The computer modeling confirmed that existing uninsulated solid masonry wall or an exterior insulated masonry wall promotes heat transfer from within the building to aid in warming and drying of the masonry wall. Also, interior insulated masonry wall reduced heat transfer from within the building to the exterior masonry and consequently, reduced the average temperature within the masonry wall and reduces the drying rate of any entrapped moisture within the wall during winter. The study demonstrated that the decrease in the average temperature of the masonry wall caused by adding insulation to the inside face of a solid masonry wall, in combination with any entrapped moisture within the wall (caused by precipitation or condensation), could promote an increased risk of freeze-thaw damage and masonry wall deterioration.

The potential for freeze thaw damage occurring with interior insulation masonry retrofits have lead to a search for an ideal strategy on how best to insulate an existing wall. One strategy includes the use of rigid foam board between the stud wall and masonry with a liquid-applied, highly vapor-permeable air and water barrier to the back of the masonry. The water barrier prevents any localized water leakage from penetrating and collecting at floor penetrations. The risk of condensation can be reduced when employing rigid foam board insulation in combination with a vapour permeable water barrier however great care must be taken during installation to prevent any gaps between the masonry and insulation that would create convective air loops for warm moist air to enter and condensate on the inside of the masonry wall [5].

Adding sprayed-on polyurethane into the stud framing of an existing brick masonry building has also been employed as an interior insulation retrofit strategy. The flexibility of the application between existing studs makes it ideal for interior insulation retrofits. However caution must be exercised with this approach as well. The insulation must promote interior drying to avoid wintertime diffusion condensation wetting. Open cell semi-permeable foams (5” has a permeance of about 13 perms should possible be considered over closed cell polyurethane foams which has a permeance of 1 perm. Similar to other strategies this solution is not perfect. Studies have shown that polyurethane foam insulation can inhibit the interior drying capability of a wood stud wall that has been exposed to moisture [6].

When dealing with an interior insulation retrofit each scenario must be studied on an individual basis to understand the real impact the insulation may have on the moisture performance of the wall. Very few studies show the relationship between recommended interior insulation retrofits and the impact on brick masonry saturation levels at or near the freezing point when freeze thaw masonry damage is most likely to occur. To avoid moisture related damage due to freeze thaw action the moisture balance of the wall system and material properties of the brick masonry should be explicitly considered during the retrofit design process. To accomplish this an understanding of the brick masonry critical degree of saturation must be included as part of the wall performance evaluation process.

The major factors affecting the occurrence and severity of frost damage can be determined from a field brick masonry sample such as moisture content during freezing, and material properties such as porosity and permeability. Developing test methods to determine the critical moisture content of a brick has been achieved in research work on frost dilatometry testing. The goal in developing the test method was to provide an estimate of the critical moisture content of brick at which it begins to experience freeze-thaw damage. The test is based upon the existence of a critical degree of saturation that when frozen expands and creates irreparable pore damage to the material. Degree of saturation is defined by Fagerlund as:

$$[\ S = V_W / V_P\ ]$$

where (V_W) is the total water volume evaporable at + 105 degrees Celsius and (V_P) is the total open pore volume before freezing. The freeze/thaw resistance is defined:

$$[F = S_{CR} – S_{ACT}]$$

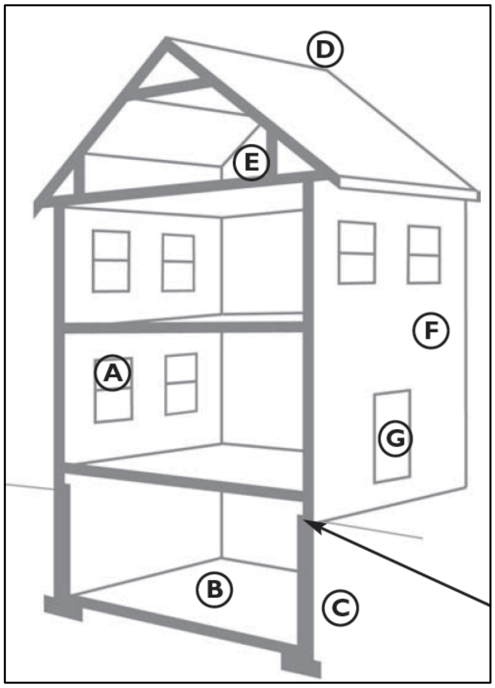
where (S_{CR}) is the critical and (S_{ACT}) the actual degree of saturation in service. S_{CR} is supposed to be independent of outer climatic conditions. It can, therefore, be regarded as a material characteristic analogous to the *fracture strength/n* static design. At moisture contents higher than (S_{CR}), the material will be seriously damaged by freezing. Below S_{CR} no damage occurs even after a large number of freeze/thaw cycles. (S_{ACT}) is the moisture content prevailing in the material at a given instant in service. (S_{ACT}) will for a certain material be a function of the way the material is utilized, of the environment and of time. (S_{ACT}) is therefore dependent on environmental and construction factors only.

3. Literature Review

The literature review explores why interior insulation of existing brick masonry buildings should be considered and what is driving the need to better understand the brick masonry freeze thaw damage risks associated with interior insulation retrofitting. The literature review then provides an overview of our current understanding of the principals involved with critical saturation of brick masonry in the field, the subsequent deterioration associated with brick masonry freeze thaw damage and the use of predictive modeling software to better understand and mitigate the likelihood of freeze thaw damage from occurring.

3.1. Insulation retrofitting of clay brick masonry buildings

Part of any major building energy retrofit includes adding insulation. Increased insulation decreases the amount of energy required by mechanical systems to heat and cool the building interior. When considering insulation retrofits of existing residential homes, property limit distances and setbacks, particularly in the Toronto area, makes interior insulation retrofitting the only viable option. The strategy of improving insulation from the interior of a brick masonry building in combination with other retrofit measures has been studied and explored in depth.



A) Windows
B) Basement Floor
C) Basement Walls
D) Ceiling
E) Roof Insulation
F) Exterior Masonry Walls
G) Exterior Doors

Figure 2 – Pre-World War II Houses – Renovating for Energy Savings (Source: CMHC, 2004)

There are several examples of studies which show the benefits of energy efficiency retrofitting of residential brick masonry buildings [7][8][9][10].The older housing stock of masonry homes in particular have strong potential for energy savings. In the US it has been estimated that homes built before 1939 consume 50% more energy than those built in 2000 [11]. It has also been calculated in the US that retrofitting 300,000 homes per year would result in saving 200 million barrels of oil energy equivalent over 10 years [12]. Much of these findings are determined with the aid of computer simulation programs. The potential energy savings can be further enhanced by combining the most effective retrofit strategies with interior insulation retrofitting for the greatest cost benefit [13]. Using simulation programs like EnergyPlus or BEopt, building models can be created and calibrated to accurately reflect actual utility consumption. Seasonal cycles in the model can be changed to reflect Actual Meteorological Year (AMY) weather files. Where discrepancies between the model energy consumption and utility billing energy consumption exist a process of normalization or fine tuning one or several of the models variables is completed until a reasonable degree of accuracy has been achieved. ASHRAE Guideline 14 is typically referenced as a model calibration standard [14]. Once a model is generated it needs to be calibrated so that modeled utility data accurately reflects actual utility monthly billing. After calibration modifications can be made to the models envelope, heating ventilation air conditioning (HVAC) and electrical systems and used to predict in field results. Results are often compared against original baseline measurements and current building code energy performance standards. In Toronto using a whole building energy model can satisfy the performance path for building code energy standards SB-10 for commercial buildings [15] and SB-12 for residential buildings [16] when applying for new construction or major renovations building permits.

In addition to practical applications simulation models can also estimate potential energy savings. In a previous study using an energy modeling program jEPlus, simulation techniques achieved an energy savings of 33% annual energy savings compared to the minimum building code requirement for a reference early 1900's 3-storey brick masonry detached house in Toronto [17]. Similar energy savings benefits can be found in different brick masonry housing archetypes as well. Using prescriptive retrofit strategies for pre-1978 homes in Chicago a study was able to achieve 54% site energy savings using the whole building energy simulator BEopt [18]. In another study energy retrofit strategies were implemented onto Toronto Century, Century-semi (typically 2-storey or 3-strorey) and War time (1-storey bungalow) masonry homes. The energy savings achieved ranged between 64% bringing the energy intensity use to 75 kWh/m^2 down from 211 kWh/m^2 [19]. The selection of retrofit strategies in these studies focused on wall insulation (interior), roof insulation, foundation wall insulation, slab insulation, window upgrades, air sealing, heating and cooling equipment and ventilation recovery.

A major risk with interior insulation retrofitting a brick masonry wall is the disruption of the walls moisture balance which can result in premature failure or brick masonry performance problems. The potential for masonry damage requires measures to be implemented to better control brick masonry exposure to moisture. Determining the best control measures to use can be a daunting task as several strategies can be employed and each strategy will have a cost and or performance impact to the proposed retrofit design. This impact to the masonry wall performance after an insulation retrofit is well documented in building science literature throughout North America and Europe.

Figure 3 – Photograph of frost damaged brick masonry and efflorescence

The addition of insulation to the interior of a load bearing masonry wall lowers the temperature gradient across the masonry and the exterior air. Both of these changes reduce the drying capacity of the masonry [20]. Internal insulation of external walls is also known to create moisture performance challenges due to increased moisture levels and condensation risk on the cold side of the insulation due to the inability of vapour impermeable insulation to transport moisture to the inner surface and allow for drying [21]. This means that during wetting periods the brick masonry wall of an interior insulation retrofit will remain saturated for longer periods of time making it more susceptible to freeze-thaw damage during winter months. To avoid these risks addressing the moisture balance issues during the retrofit design phase becomes critical.

3.2. Determining Critical Saturation as a Metric to Assess Freeze Thaw Damage Risk

Understanding risks of brick masonry freeze thaw damage has often been studied under the umbrella of brick masonry durability. The information gathered from field performance monitoring can be used to develop a durability index that details the limiting values that separate durable from nondurable bricks [22]. It is difficult to develop these indices as it takes many years to collect data from field performance studies. Therefore exposing clay brick masonry samples to laboratory durability testing is often employed. When it comes to the freeze thaw damage durability of clay brick several tests to better understand its durability have been developed.

Table 1 – Brick Masonry Testing Methods - Koroth, S. R. (1997)

Test Procedure	Purpose
▪ Water Absorption Test	Provide a rough estimate of the porosity of the brick and the degree of saturation attained by the specimens
▪ Capillary Absorption Test	Measures the amount of water absorbed by the brick specimens through capillary action.
▪ Submersion Test	24 hr absorption value is commonly used to determine the maximum amount of water that can be absorbed under normal circumstances (ASTM C67) [23]
▪ Boiling Absorption Test	Used to determine the maximum amount of water a clay brick masonry specimen can hold or the maximum saturation limit where all pores are filled with water.
▪ Vacuum Saturation Test	Used to determine the maximum amount of water a clay brick masonry specimen can hold or the maximum saturation limit where all pores are filled with water.
▪ Mercury Intrusion Porosimetry	Used to determine porosity and pore size distribution.
▪ Ultrasonic Pulse Velocity Test	Used to find relation between brick properties and the velocity of the transmitted pulse coming through the material.
▪ Freeze Thaw Testing	Used to determine freeze thaw durability of clay brick sample (ASTM C67)

The most notable and widely referenced durability tests can be found in American and Canadian Standards for measuring the durability and resistance to freeze thaw damage, ASTM (C62-05, C216-07a) [24] and CAN/CSA (A82-06) [25]. The results from the testing lead to the classification of clay brick masonry into three categories:

- *Grade NW (Negligible Weathering)* – Bricks with little resistance to cyclic freezing damage but which are acceptable for applications protected from water absorption and freezing.
- *Grade MW (Moderate Weathering)* – Brick intended for use where moderate resistance to cyclic freezing damage is permissible or where the brick may be damp but not saturated with water when freezing occurs.
- *Grade SW (Severe Weathering)* – Brick intended for use where high and uniform resistance to damage caused by cyclic freezing is desired and where the brick may be frozen when saturated with water.

Table 1. Exterior Grade/Severe Weathering Acceptance Criteria from CSA and ASTM Standards

	Compressive Strength		Max. Boiling Absorption 5-Hour, %	Max. Saturation Coefficient	Max. 24-Hour Cold Absorption
	MPa	psi			
CSA individual brick	17.2	—	17.0	0.78	8.0
Five-brick average	20.7	—	—	—	—
ASTM individual brick	17.2	2500	20.0	0.80	8.0
Five-brick average	20.7	3000	17.0	0.78	—

Figure 4 - Brick Masonry Acceptance Criteria. Straube, Schumacher, Mensinga 2010

Both standards rely on the assumption that resistance to freeze thaw is based on the need to provide an adequate amount of open-pore space to accommodate the expansion of water as it freezes. The shortcoming with the testing standards is the results experienced in the field and the tests acceptance criteria do not always correlate. A brick masonry unit can still experience freeze thaw damage in the field where it would pass the CSA and ASTM standard criteria or fail the standards criteria and perform adequately in the field [26]. The same problems exist with the Standard's alternate means of passing. In the event that a brick masonry sample fails the criteria standard it can still be passed based on a pass / fail grade after a 50 cycle freeze thaw test alternative where the brick must be able to maintain more than 3% mass loss for ASTM and 5% mass loss for CSA) and not show signs of visual cracks. Neither of these approaches considers the saturation point needed for freeze thaw damage to occur and therefore cannot be used as a reliable basis for predicting future performance in the field.

The concept of porous building materials having a critical saturation point was initially developed using concrete cylinders as the test material [27]. Frost damage was assessed by exposing concrete cylinder samples to varying degrees of saturation followed by a series of freeze / thaw cycles. Freeze thaw damage was assessed by measuring changes in e-modulus or length change. The results showed that for each sample a specific amount of saturation was required before freeze thaw damage would occur and that saturation level required for freeze thaw damage to occur is an inherent property of the concrete sample. The exact property which contributes to a materials critical level of saturation is still a topic of study. Both concrete and clay brick masonry tests have shown that critical saturation appears to be independent of air content [28] and pore size [29]. It is also still uncertain whether the amount of moisture that can be absorbed based on pore size impacts the materials critical saturation point. Despite these facts the critical saturation test method developed identify several important factors that must be determined when analyzing brick masonry freeze thaw damage [a]. The most important factor being the critical degree of saturation [b], or the ratio of maximum water that can be held in the material (S_{CAP} or W_{MAX}) [c] to the amount of water held in the material when it is in a saturated state and freeze thaw damage occurs (S_{CRIT}). With this information a more accurate definition of freeze thaw resistance [d] can be determined. Not all degrees of saturation [e] are harmful to the performance of porous building material at the point of a freeze thaw cycle. Knowing the difference between the degrees of saturation a material can safely store and the critical degree of saturation of porous material such as concrete or brick masonry is of great importance when considering an interior insulation retrofit and the potential moisture performance issues it may encounter when in service. This importance was highlighted in studies that further expanded the testing methods established by Fagerlund. Focusing on brick masonry, Mensinga proposed that a more useful approach to assessing the risk of damage due to freeze-thaw than current ASTM and CSA standards [30][31][32] would be to determine the critical degree of saturation of the brick masonry and then compare that to anticipated moisture loads under service conditions using computer modelling software such as WUFI [33]. Frost dilation [f] was used to define the physical process of freeze thaw damage. Frost dilation was measured using frost dilatometry testing [g] and recorded in units of microstrain [h] using two dimensional reference points. Where microstrain occurred passed a threshold limit (irreversible damage measured at 100 Microstrain or greater) freeze thaw damage can be said to have occurred and the brick masonry test samples critical degree of saturation found.

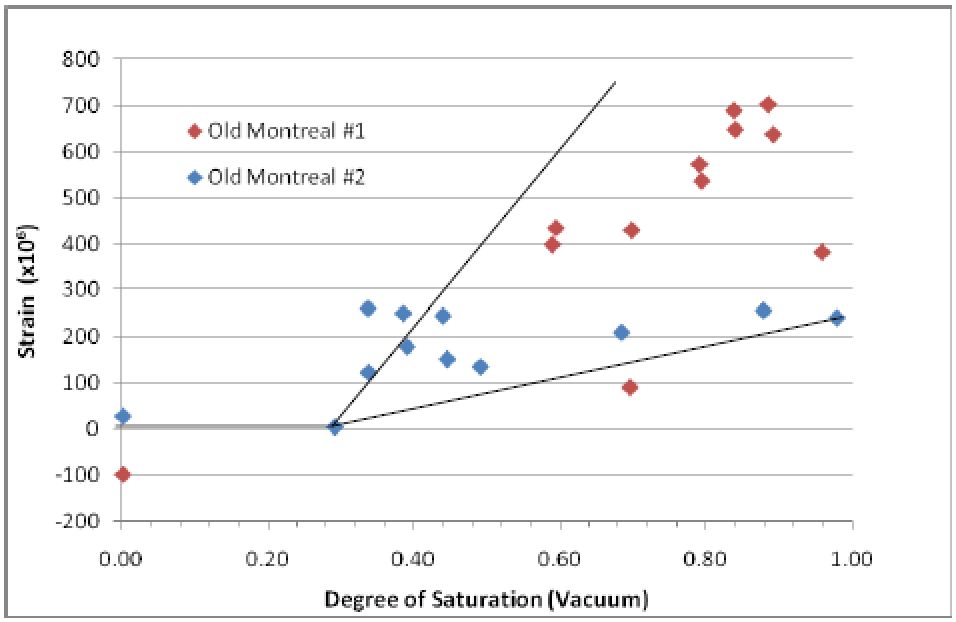


Figure 5 – Frost dilatometry: Old Montreal brick. Mensinga, P. 2009.

Another study on critical saturation by Williams expanded frost dilatometry testing and included three dimensional measurements of frost dilation to determine (S_{CRIT}). Seasonal changes to brick masonry wall temperature and moisture load was gathered using in situ embedded sensors. With both annual moisture load and temperature data the amount freeze thaw cycles or zero degree crossing occurrences could be compared to critical saturation periods. Any overlap indicated the potential for freeze thaw damage to occur and an assessment of the relative durability of the brick masonry wall was made [34]. The study determined that the subject masonry wall was expected to have a low probability of freeze thaw damage. The in situ measured moisture load that was recorded during zero (0) degree crossing temperature periods was half the amount required for the masonry to be considered critically saturated. Measured moisture load readings taken from embedded sensors amounted to a degree of saturation of 29% M.C. compared to frost dilatometry tested (S_{CRIT}) values for the brick masonry which ranged between a degree of saturation of 70% to 80% M.C. Ongoing monitoring of the building will have to be made to verify the findings over time, however if validated these methods can be used for a much wider application of buildings and potentially contribute towards the development of a comprehensive clay brick masonry freeze thaw durability index.

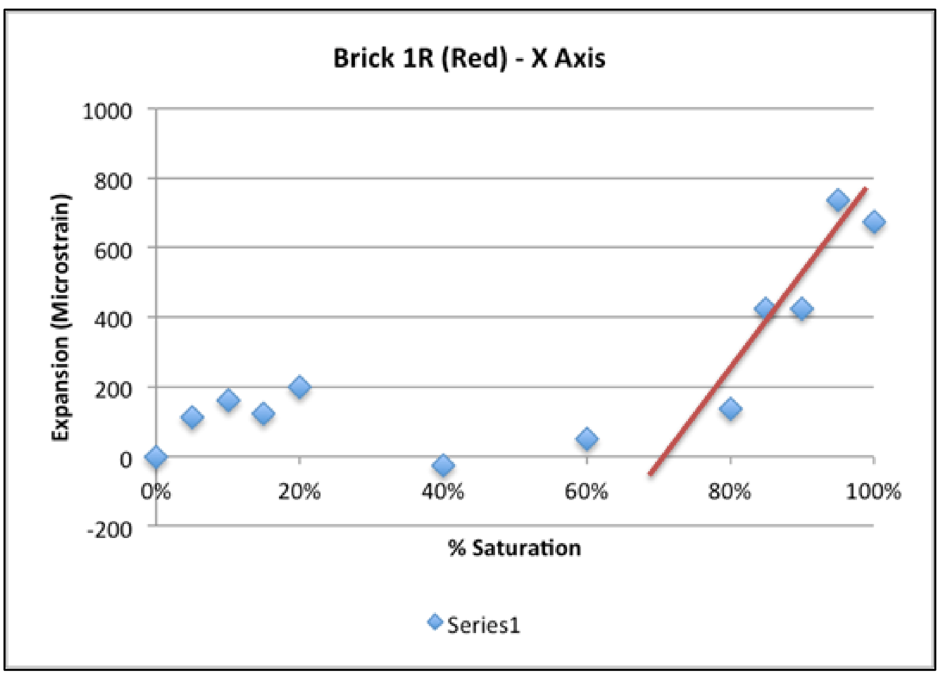


Figure 6 – Frost dilatometry: Red Brick. Williams, B. 2014.

The use of dilatometry testing demonstrates that a critical degree of saturation exists in clay brick masonry. The cumulative research demonstrates a clear saturation threshold where if below, irreversible expansion due to frost damage does not occur and above irreversible expansion of brick masonry (100 Microstrain) occurs. (S_{CRIT}) is clearly seen when dilation of samples is plotted against its moisture content during freeze-thaw cycling.

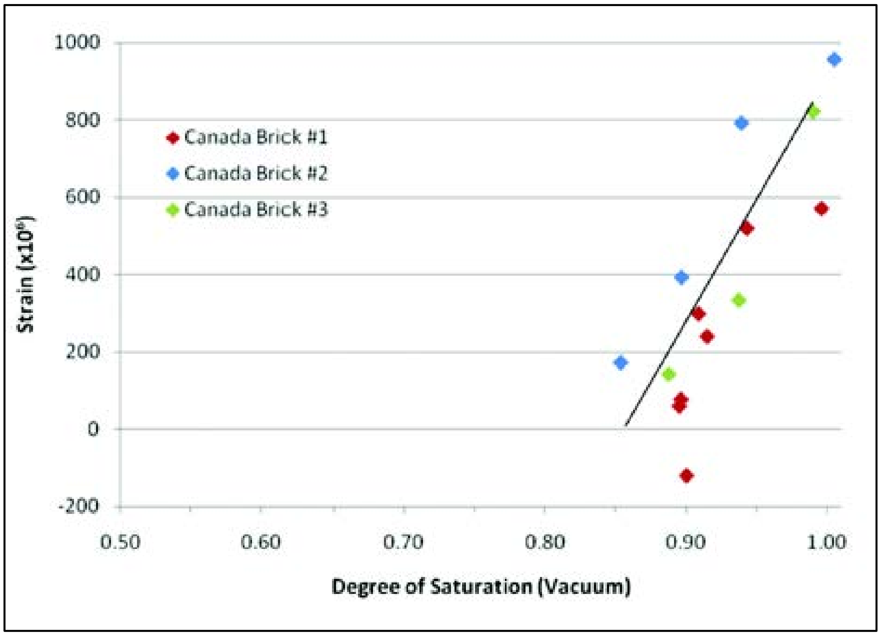


Figure 7 – Frost dilatometry: Canada brick. Straube, J., et al. 2010.

In the studies the thresholds can vary among bricks [35]. Those bricks with high porosity and high absorption value had a low critical degree of saturation whereas those bricks with low porosity and low absorption value had a high critical degree of saturation. Further testing is needed to determine if this relationship is consistently observed in clay brick masonry. The key factor is that Frost dilatometry can be used to reliably determine the critical degree of saturation at which freeze-thaw damage is likely to occur in brick masonry unit samples. Challenges with regards to in situ testing still remain. Based on the current limitations of embedded moisture sensor technology (EMS) precision critical saturation moisture levels are extremely difficult to measure in the field. This short coming makes it difficult to validate laboratory testing with in field measurements.

3.3. Coupling Scrit Measurement with Predictive Modeling Hygrothermal Performance to Assess the Risk of Freeze Thaw Deterioration

The majority of the literature reviewed that used hygrothermal modeling to better understand the impacts insulation retrofits have on the moisture performance of a masonry wall focused on preventing condensation, bio deterioration, mould growth or on analyzing the results of in situ temperature and moisture measurements in the field or through controlled lab experiments [36][37][38][39].

In one study using WUFI, efforts were made to minimize the moisture content of an insulation retrofitted historical masonry wall assembly and promote drying to the interior. The insulation materials consisted of autoclaved aerated concrete (AAC), calcium silicate board (CaSi) and a capillary active thermal insulation system based on rigid PUR-foam panels made capillary active by adding mortar channels (IQ-Therm). The vapour permeable insulation was tested with different insulation thicknesses (30–100 mm) and with or without driving-rain protection. The brick masonry rain protection wsa simulated by reducing the models brick masonry rain water absorption to 1%. The 1% was used to simulate a crack in the brick masonry where some moisture would still be able to penetrate. The retrofit strategy was able to reduce the moisture content of the wall caused by driving rain and lack of interior drying capability [40]. The use of vapour permeable insulation wall had relatively low thermal resistance values ranging from R0.97 to R2.69 making it less ideal from an energy performance perspective. The key finding was that without the impregnated water barrier the vapour permeable insulation alone resulted in high relative humidity levels on the interior surface of the wall and risk of mould growth. This drawback and risk was also confirmed in a study performed on a historical masonry school building retrofitted with vapour permeable insulation. The data was analyzed through a combination of in situ temperature and RH measurement and hygrothermal modeling program DELPHIN 5.8.1. The results showed high humidity and possible condensation occurrence in all vapour permeable insulation scenarios [41]. Freeze thaw damage potential and critical saturation was not addressed in this study.

In another study by Johansson et al the interior insulation retrofitted wall analysis included an assessment of freeze thaw damage potential. The insulation material consisted of vacuum insulation panels (VIP). Another option for an interior insulation retrofit that can be used when looking to minimize the U-Value of the wall assembly and reduce energy consumption. This study was performed in a laboratory setting and combined in situ measurement with hygrothermal modeling program WUFI 2D. The benefits of VIP include a lesser thickness to reach the same thermal resistance of other insulation products. The use of vacuum insulation panels on the inside of brick masonry wall can reduce the energy use of the building due to its high RSI value however the numerical simulations revealed that the wall could be damaged by freeze-thaw action on the exterior brick surface at areas exposed to driving rain due to the walls reduced drying capacity. The bricks selected were taken from two building existing known to have experienced Freeze thaw damage. The addition of the VIP’s was assumed to contribute to an increased potential for freeze thaw damage. The assumption was made since the critical saturation of the brick was not part of the studies scope of work. In the study the moisture content accumulation in the wall was highly influenced by the material properties of the brick and mortar samples that were used versus the addition of insulation which was shown to have had more of an influence on the drying rate of the wall [42].

Morelli and Svendsen focused on one of the design challenges that face interior insulation retrofits of brick masonry construction [43]. The study presented a method to investigate retrofit measures of interior-insulated masonry walls having wooden floor beams based on a failure mode and effect analysis (FMEA) combined with hygrothermal simulations. The method was first used to determine the potential for failure in retrofitted walls and their effects and causes, and thereafter, the expected hygrothermal performance of the retrofit measures was further investigated using both thermal and hygrothermal simulation software. The results show that the risk to incurring moisture problems at the wooden beam ends can be resolved by not insulating that portion of the wall directly above and below the floor division. The changes also effectively reduced the heat loss of the original wall structure by half. In this study the authors looked at the critical moisture content required for wood decay but not for brick masonry freeze thaw damage.

Sedlbauer and Kunzel identified determining factors associated with the risk of brick masonry freeze thaw damage [44]. The proposed factors include the quantity of below zero occurrences and the moisture content of the specimen. Frost damage occurs especially if damp building elements are subjected to frequent freeze-thaw cycles. The observation that frost damage can also be frequently observed in warmer winters confirms that one cannot use the outside air temperature level as the only criterion, but that the combination of the number of freeze-thaw cycles in the building element's interior and the moisture content in the material at those times must also be considered. The number of zero crossings on a Celsius scale during each half year of the winter, and the corresponding moisture content profiles were calculated using WUFI. The effect of different meteorological conditions on zero crossings and material moisture has been determined using meteorological data measured during several years at the Fraunhofer-Institute for Building Physics (IBP) outdoor testing field. From the results, the authors proposed it is possible to assess the frost damage risk. It is important to note that critical saturation was not used in this study, instead, empirical studies of similar brick masonry units and their freeze thaw performance was used as a reference for critical moisture saturation content. The conclusion from the hygrothermal analysis was that large differences in the number of zero crossings as well as in the corresponding moisture levels in the building element arise depending upon the climate acting on the element.

While these studies highlight the moisture performance concerns related to interior insulation retrofits they do not couple (S_{CRIT}) measurement with the hygrothermal modeling techniques to determine potential for freeze thaw damage as suggested by Mensinga. One of the first studies to do this was completed by Ueno, Straube and Van Straaten [45]. In the study a 1917 masonry building located on a Boston-area university campus that was retrofitted with interior polyurethane spray foam insulation was analyzed. Sensors were installed in the retrofitted walls to measure temperature and moisture conditions as well as interior and exterior boundary conditions. Hygrothermal simulations were run in parallel on the original and retrofitted assemblies using measured site environmental data, both to assess durability risks, and for comparison with the measured data. Measured data indicated that the insulated masonry walls were colder and had higher moisture contents than uninsulated assemblies. Hygrothermal simulations had good correlation to temperature measurements, but moisture measurements were less consistent. The simulations indicated a low risk of freeze-thaw damage based on (S_{CRIT}) values calculated by outside consultants compared with in situ moisture measurements taken. In another study known (S_{CRIT}) values combined with WUFI hygrothermal modeling to establish a limit states approach to insulating solid masonry walls as it relates to both freeze thaw damage and corrosion deterioration mechanisms [46]. In the study an institutional building and museum located in Ontario were candidates for interior insulation retrofits were analyzed. (S_{CRIT}) values were determined via frost dilatometry testing. The simulations indicated the masonry walls for both buildings were at low risk of freeze-thaw damage based on calculated free water saturation values compared to critical saturation values and site observations showing the brick masonry to be in good condition even at areas of high exposure to rain.

While there have been many studies on the benefits of insulation retrofitting existing masonry buildings from an energy / cost benefit perspective or on how best to manage moisture loading and water tightness of a brick masonry wall [47][48][49][50] very few studies, as shown in the literature review, have analyzed the relationship between increasing interior insulation in an existing masonry wall and its impact on the increased moisture content of the masonry wall as it approaches a critical saturation limit. The closer the wall comes to critical saturation during freeze thaw temperature ranges the higher the potential will be that the wall will experience freeze thaw damage. Except for two of the literature studies reviewed which used WUFI for predictive modeling of masonry insulation retrofits, (S_{CRIT}) was typically not taken into account. Without taking (S_{CRIT}) into consideration any recommendation for an insulation retrofit has to still be considered a potential risk for freeze thaw damage.

4. Methodology

The brick masonry wall construction studied is from a Pre-World War 2 residential building in Toronto, Ontario. Values for the material properties and brick masonry critical saturation was collected from a previous research study by Williams. These values were input into WUFI to generate a baseline model that could be compared to 8 other insulation types. The insulation types were selected based on previous literature studies which used the insulation materials to complete interior insulation retrofits. All options had varying thermal and moisture performance properties. A 2013 Toronto weather file was used to simulate the Actual Meteorological Year (AMY).

The WUFI data results from running the wall system options was used to analyze the impact the insulation materials had on the brick masonry moisture absorption over a one year period. Times of the year where brick masonry zero degree crossings or freeze thaw cycles occurred were recorded and compared to corresponding moisture content (kg/m3) levels. Critical saturation is identified as a moisture content level and as a ratio to max saturation *(S_{MAX})* for ease of comparison. A freeze thaw resistance metric originally proposed by Fagerlund [$F = S_{CRIT} – S_{ACT}$] was used for comparing the insulation options moisture content levels at the point of a freeze thaw cycle. Its ratio to max saturation *(S_{MAX})* was to compare which insulation options were more likely to contribute to brick masonry freeze thaw damage. The data was further analyzed to determine which insulation option provided the highest amount of thermal resistance when compared to its contributing risk to brick masonry freeze thaw damage.

4.1. Subject Building

The results generated came from analyzing the Subject Pre-World War 2 Residential Building wall construction.

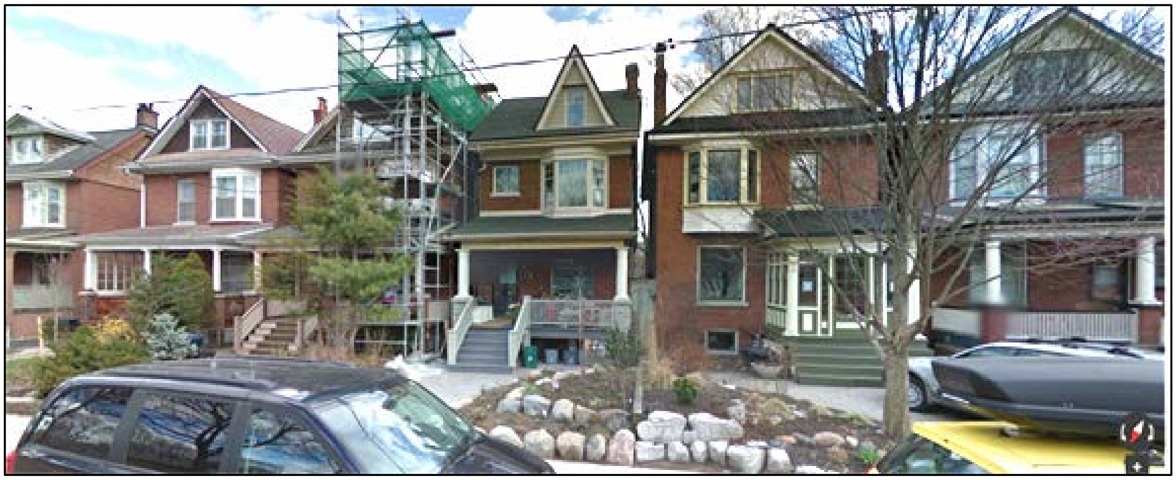


Figure 8 – Subject Residential Building Pre WW2 Archetype

The building is wood framed with 38 mm x 63 mm wood studs and finished on the interior with 16 mm gypsum board. The exterior masonry consisted of double whyte 200 mm brick masonry. The residential building had undergone an interior insulation retrofit in 2010 that included the installation of 138 mm to 190 mm of 900 g (2-lb) closed cell spray applied polyurethane foam insulation onto the interior face of the exterior clay brick masonry walls. Values for the brick material properties has been collected from frost dilatometry testing by Williams. These values were input into WUFI as the baseline 1D model from which other interior insulation retrofit options were compared against.

Table 2 – Baseline 1D wall properties for Subject Study building in Toronto, Ontario

	Brick	GWB	PUR
▪ *Bulk density, kg/m3*	1665	625	39
▪ *Thermal conductance W/(m2 . K)*	2	10	0.16
▪ *Thermal resistance (m2 . K)/ W*	0.5	0.1	6.25
▪ *Porosity (m3/m3)*	0.394	0.706	0.99
▪ *Vapor diffusion resistance coefficient*	16	7.03	88.93
▪ *Water absorption coefficient (kg/m2/s^0.5)*	0.6	-	-
▪ *Typical built in moisture (kg/m3)*	2	8.65	1.12

- *Indicate values that are approximated by WUFI*

4.2. WUFI Weather Files

Weather files in WUFI can be customized to meet actual seasonal cycles or Actual Meteorological Year (AMY) weather files. This gives the ability to analyze the brick masonry performance to typical seasonal exposure to moisture and temperature variations or select scenarios where temperature variations and moisture loads (kg/m^3) are increased. For this study Toronto 2013 AMY weather files were used as the weather baseline for the outdoor climate. A consistent weather pattern for the study was important. From the weather file WUFI further allows the user to modify the interior climate conditions by either increasing the relative humidity from a normal moisture load to a high moisture load. For the purpose of keeping all the scenarios consistent a normal relative humidity setting was selected.

4.3. Baseline Clay / Shale Brick Masonry and Wall Data

Previous frost dilatometry testing of the brick masonry by Willliams provided the brick masonry properties that were inputted into WUFI. These values are critical for any serious analysis of the potential for brick masonry freeze thaw damage as it will give the maximum amount of moisture content (kg/m3) a brick masonry sample can contain without experiencing freeze thaw damage. According to the frost dilatometry testing the degree of critical saturation of the masonry wall is between 70% M.C. to 80%. This value is in line with data collected by Van Straaten and Building Science Labs which shows a range of existing North American clay / shale brick masonry units tested between the years 1830 and 1950 of critical saturation values as low as 38% and as high as 90% [51]. Density of the brick was determined using the dry weight of a brick masonry sample. Porosity was measured by both boiling water and vacuum test methods. The water absorption coefficient was determined by following test method procedure ASTM C67-11, 10.3 while free water saturation, super saturation and critical saturation were determined by frost dilatometry testing. With these known values a relatively accurate model of the brick masonry can be analyzed in WUFI.

Table 3 – Brick masonry properties for Subject Study building in Toronto, Ontario

	Brick Frost dilatometry [52]
▪ *Bulk Density (Kg/m^3)*	1665.30
▪ *Porosity (m^3 / m^3)*	0.394
▪ *Free water saturation (kg/m^3)*	241.54
▪ *Super saturation (kg/m^3)*	353.84
▪ *Water absorption coefficient (kg/m2/s^0.5)*	0.6
▪ *Critical Saturation S_{CRIT} (kg/m^3) or (%)*	247.69 or 70%

4.4. Interior Insulation Retrofit Options

Based on examples from the literature [53][54] eight (8) interior insulation retrofit scenarios were modeled in WUFI PRO 5.3. to determine their impacts on the moisture performance of the brick masonry wall. Where values were not provided in the literature references WUFI approximation values were substituted. The selection of insulation materials varies in composition and thermal conductivity values. The first set of values evaluated in WUFI included mineral wool (MWL), fiberglass (FBG), expanded polystyrene (EPS) and a combination of polyurethane foam and cellulose fibre insulation (Hybrid). Each option was added in WUFI to have the same 150 mm thickness of insulation. The Hybrid option was divided between 50% cellulose fibre and 50% polyurethane foam insulation. The insulation values range between R4.16 and R5.11. The number of freeze thaw cycles experienced in these interior insulation retrofit options vary between 23 and 25. The maximum moisture content experienced at a zero degree crossing varies between 65.77 kg/m^3 on the low end and 68.07

kg/m^3 on the higher end. The freeze thaw resistance for each option however is relatively the same at approximately 73%.

Table 4 – Straube [55] - Final guideline measures

	Hybrid	MWL	FBG	EPS
▪ *Bulk density, kg/m^3*	34.5	71	30	14.8
▪ *Thermal conductance W/(m^2 . K)*	0.19	0.21	0.23	0.24
▪ *Thermal resistance (m^2. K)/ W*	5.11	4.76	4.34	4.16
▪ *Porosity (m3/m3)*	0.99	0.95	0.99	0.99
▪ *Vapor diffusion resistance coefficient*	45.39	1.1	1.3	73.01
▪ *Water absorption coefficient (kg/m^2/s^0.5)*	-	-	-	-
▪ *Typical built in moisture (kg/m^3)*	1.12	1.12	1.12	1.12
▪ *Number of freeze thaw cycles*	25 *	23 *	24 *	25 *
▪ *Max moisture content S_{ACT} at freeze thaw cycle (kg/m^3)*	66.78	68.07	67.67	65.77
▪ *Freeze thaw resistance (Scrit - Sact) as a % of Scrit*	73%	73%	73%	73%

\- *Indicate values that are approximated by WUFI*

* *Outer whyte of brick masonry*

The next set of insulation options was gathered by Kloseiko and includes a mix of open porosity low vapor diffusion resistant insulation and high vapour diffusion resistance insulation polyisocyanurate board (PIR), polyurethane board with capillary active channels (IQ-T), aerated concrete (AAC) and calcium silicate (CaSi). The insulation values range between R2.27 and R7.69. The number of freeze thaw cycles experienced in these interior insulation retrofit options vary between 18 and 25. The maximum moisture content experienced at a zero degree crossing varies between 62.79 kg/m^3 on the low end and 82.79 kg/m^3 on the higher end. The freeze thaw resistance for each option also varies between 67% and 75%.

Table 5 – Kloseiko[56] - open porosity low vapour diffusion resistance vs high vapour diffusion resistance

	PIR	IQ-T	AAC	CaSi
▪ *Bulk density, kg/m³*	35	49	126	297
▪ *Thermal conductance W/(m² . K)*	0.13	0.19	0.3	0.44
▪ *Thermal resistance (m². K)/ W*	7.69	5.26	3.33	2.27
▪ *Porosity (m3/m3)*	0.99	0.99	0.79	0.9
▪ *Vapor diffusion resistance coefficient*	400	51	6	11
▪ *Water absorption coefficient (kg/m²/s^0.5)*	0.1^{-7}	0.013	0.0036	0.39
▪ *Typical built in moisture (kg/m³)*	1.12	1.12	1.12	1.12
▪ *Number of freeze thaw cycles*	25	26	23	18
▪ *Max moisture content S_{ACT} at freeze thaw cycle (kg/m³)*	82.79	66.73	65.42	62.7 9
▪ *Freeze thaw resistance (Scrit - Sact) as a % of Scrit*	67%	73%	74%	75%

- *Indicate values that are approximated by WUFI*

* *Outer whyte of brick masonry*

4.5. Critical Saturation Resistance

Temperature and moisture content monitoring positions in WUFI were placed in both the inner and outer whyte of brick masonry in order to detect zero degree crossings. The number of zero degree crossings was unique for each insulation option due to the changes in temperature profile the insulation has on the exterior wall. Zero degree crossings were also more predominant at the outer brick whyte layer due to exposure to exterior cold weather temperatures and therefore the outer layer is what was used for comparing the nine (9) different interior insulation options. The more occurrences of zero degree crossings in the brick masonry further increases the potential for freeze thaw damage to occur in the assembly. However the relationship between the amount of zero degree crossings and freeze thaw damage is not dependent. The critical measure of freeze thaw damage is the actual moisture content of the brick masonry at the time of a zero degree crossing occurrence. To determine the number of zero degree crossings and moisture content at the point of the crossing further analysis of the WUFI output data had to be completed. To accomplish this the hourly recorded data produced by modeling each insulation option in WUFI was converted from a WUFI ASC file into a spreadsheet where further analysis of the results using pivot tables and data filtering could be performed.

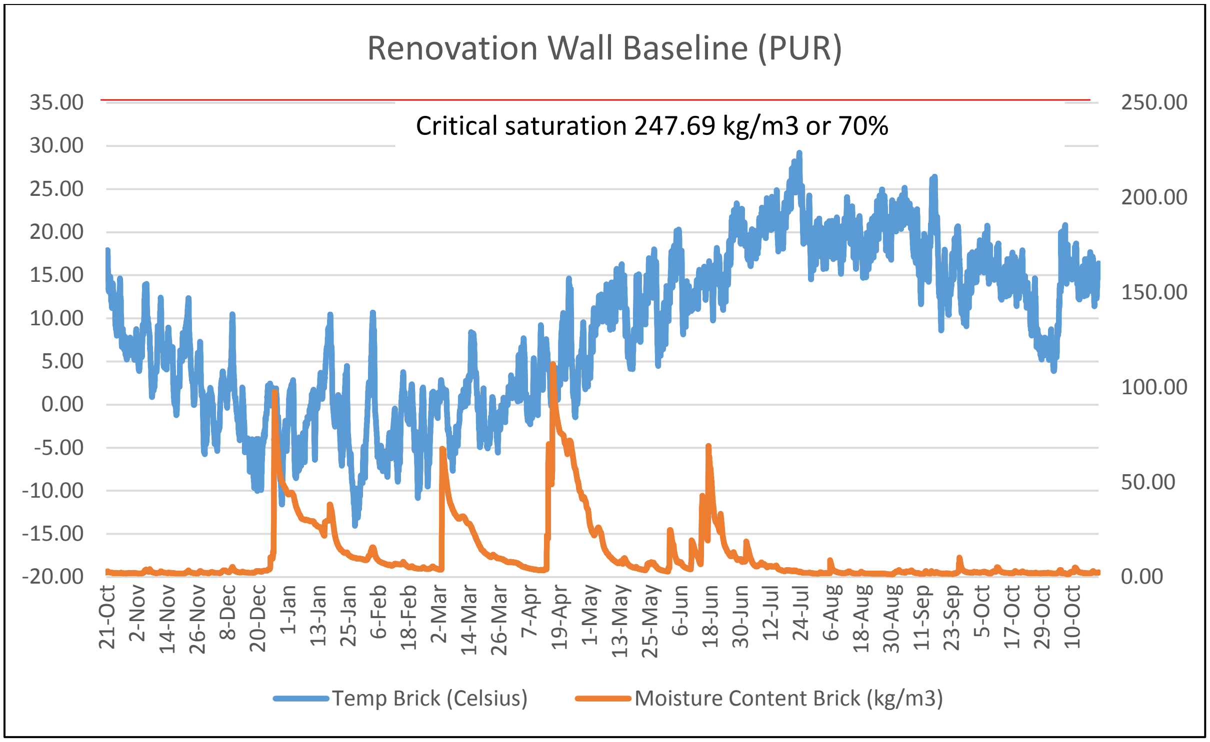


Figure 9 – Original renovated wall seasonal moisture performance

For each insulation option a total of 9504 hourly temperature and moisture content readings were produced by WUFI. Once this data was transferred to a spreadsheet, a series of computational algorithms were used to organize and sort the desired data. Both moisture and temperature data could then be plotted against the calendar dates for the Toronto AMY for 2013. The next step in the data sorting was to identify how may zero degree crossings occurred over the total 9504 hours of the study year. Within the data set zero degree crossings (where zero degrees was crossed moving up and down in temperature were identified by using algorithms:

a) IF(SIGN(C8)<>SIGN(C7),IF(SIGN(C8)<SIGN(C7),MAX($H$2:H7)+1,""),"") and IF(SIGN(C8)<>SIGN(C7),IF(SIGN(C8)>SIGN(C7),MAX($I$2:I7)+1,""),"").

The sum total giving the total amount of zero degree crossings modeled for the year where freeze thaw damage could occur if the brick masonry were critically saturated. To determine what the moisture content was at the time of the zero degree crossing and whether it was close to the critical saturation point the following algorithm was used:

b) IF(SIGN(C4)<>SIGN(C3),AVERAGE(E3:E4),"").

This formula would identify the occurrence of the zero degree crossing and then take the average moisture content between the current moisture content state point where the zero degree crossing occurred and the previous hour to get the average moisture content that likely occurred at the point of freezing.

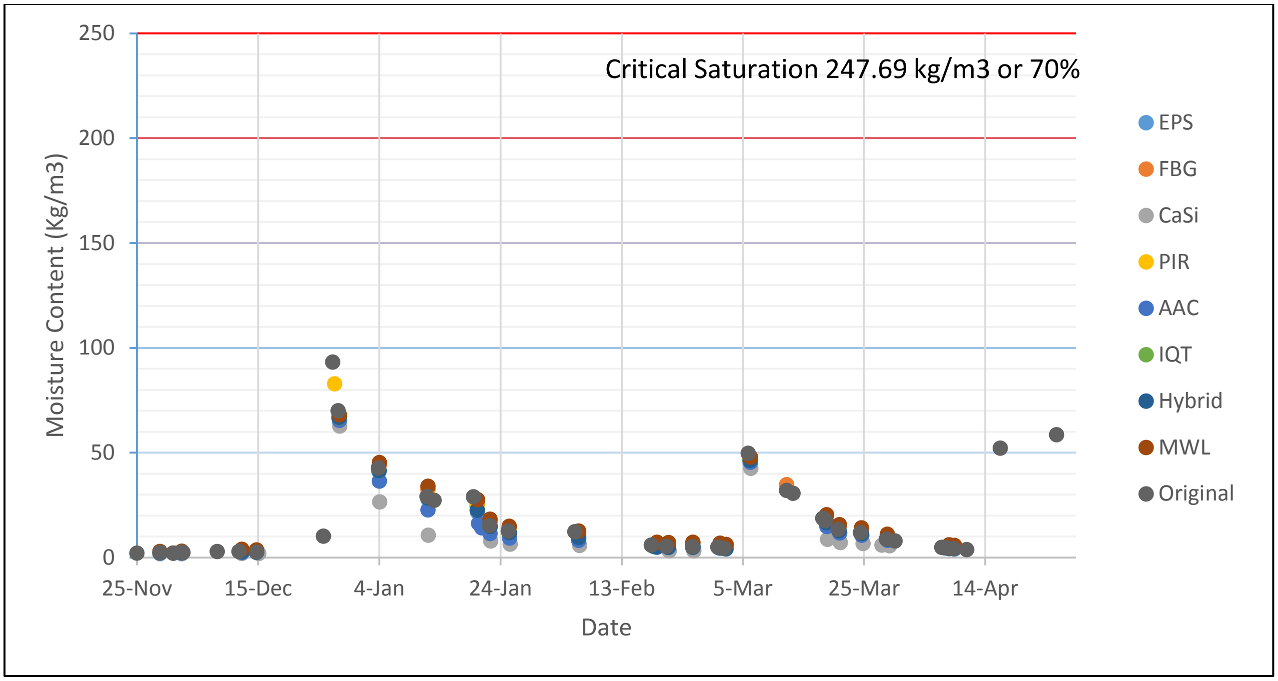


Figure 10 – Moisture Content at Zero Degree Crossing for Insulation Options

The metric used to determine freeze thaw resistance comes from Fagerland as the difference between critical saturation and actual saturation or moisture content measured at specific point in time [$F = S_{CRIT} - S_{ACT}$]. The resistance was then converted to a percentage of critical saturation to make for simple comparisons of which insulation option had the highest resistance to freeze thaw damage. The higher the percentage or the greater the difference between moisture content (S_{ACT}) and (S_{CRIT}) the less likely the brick masonry would experience freeze thaw damage and alternatively the lower the percentage or the closer (S_{ACT}) came to (S_{CRIT}) would result in a greater potential that freeze thaw damage would be experienced by the brick masonry during the zero degree crossing. For the purpose of this study the specific point in time (S_{ACT}) referenced was selected from the weather files zero degree crossing and the maximum moisture content experienced during one of the several annual zero degree crossing events. From this information it was possible to graph all zero degree crossing occurrences and the moisture content of the outer and inner whyte of brick at the time of the zero degree crossing over the a calendar year for each interior insulation retrofit option. The first option being the baseline renovated wall construction consisting of spray foam polyurethane insulation. The baseline insulation value was R6.25. For the baseline wall condition there are a total of forty (40) freeze thaw cycles experienced in the calendar year. The maximum moisture content at the time of the zero degree crossing is 93.23 kg/m^3. When compared against the moisture content required for freeze thaw damage to occur this gives the assembly a freeze thaw resistance of approximately 62%.

Table 6 – Renovation Baseline Freeze Thaw Resistance

	Brick	GWB	PUR
▪ *Bulk density, kg/m^3*	1665	625	39
▪ *Thermal conductance W/(m^2 . K)*	2	10	0.16
▪ *Thermal resistance (m^2. K)/ W*	0.5	0.1	6.25
▪ *Porosity (m3/m3)*	0.394	0.706	0.99
▪ *Vapor diffusion resistance coefficient*	16	7.03	88.93
▪ *Water absorption coefficient (kg/m^2/s^0.5)*	0.6	-	-
▪ *Typical built in moisture (kg/m^3)*	2	8.65	1.12
▪ *Number of freeze thaw cycles*	40 *	Na	Na
▪ *Max moisture content S_{ACT} at freeze thaw cycle (kg/m^3)*	93.23	Na	Na
▪ *Critical Saturation resistance (Scrit - Sact) as a % of Scrit*	62%	Na	Na

- *Indicate values that are approximated by WUFI*
* *Outer whyte of brick masonry*

5. Discussion

The findings from the WUFI analysis show that for the first set of insulation options in Table 5 which include Hybrid, mineral wool (MWL), fiberglass (FBG) and expanded polystyrene (EPS) the number of freeze thaw cycles (23-25) and freeze thaw resistance (73%) remains relatively the same. The insulation values between the options are also very similar, the largest difference between the set being the R5.11 of the Hybrid option and R4.16 of the EPS option.

For the second set of insulation options in Table 6 which include polyisocyanurate board (PIR), polyurethane board with capillary active channels (IQ-T), aerated concrete (AAC) and calcium silicate (CaSi) the number of freeze thaw cycles (18-26) and freeze thaw resistance (67% to 75%) shows a relatively large difference. The insulation values between the options are also different, the largest difference between the set being the R7.69 of the (PIR) option and R2.27 of the (CaSi) option. For the second set of insulation values analyzed there does appear to be a relationship between the insulation R value and potential for freeze thaw damage measure in freeze thaw resistance as the higher R value found in (PIR) produced the lowest resistance to freeze thaw damage at 67%.

This result is also similar in the baseline model where the polyurethane spray foam insulation with a higher R value of R6.25 produced a lower resistance to freeze thaw damage at 62%. The relationship between the R value and freeze thaw resistance however is not perfectly linear as shown in Table 7. However there is a general relationship between the two factors which cannot be ignored.

Table 7 – Relationship between insulation value and critical saturation resistance

Option	R Value	Critical Saturation Resistance *(Scrit - Sact) as a % of Scrit*
PIR	7.69	67%
PUR	6.25	62%
IQ-T	5.26	73%
Hybrid	5.11	73%
MWL	4.76	73%
FBG	4.34	73%
EPS	4.16	73%
AAC	3.33	74%
CaSi	2.27	75%

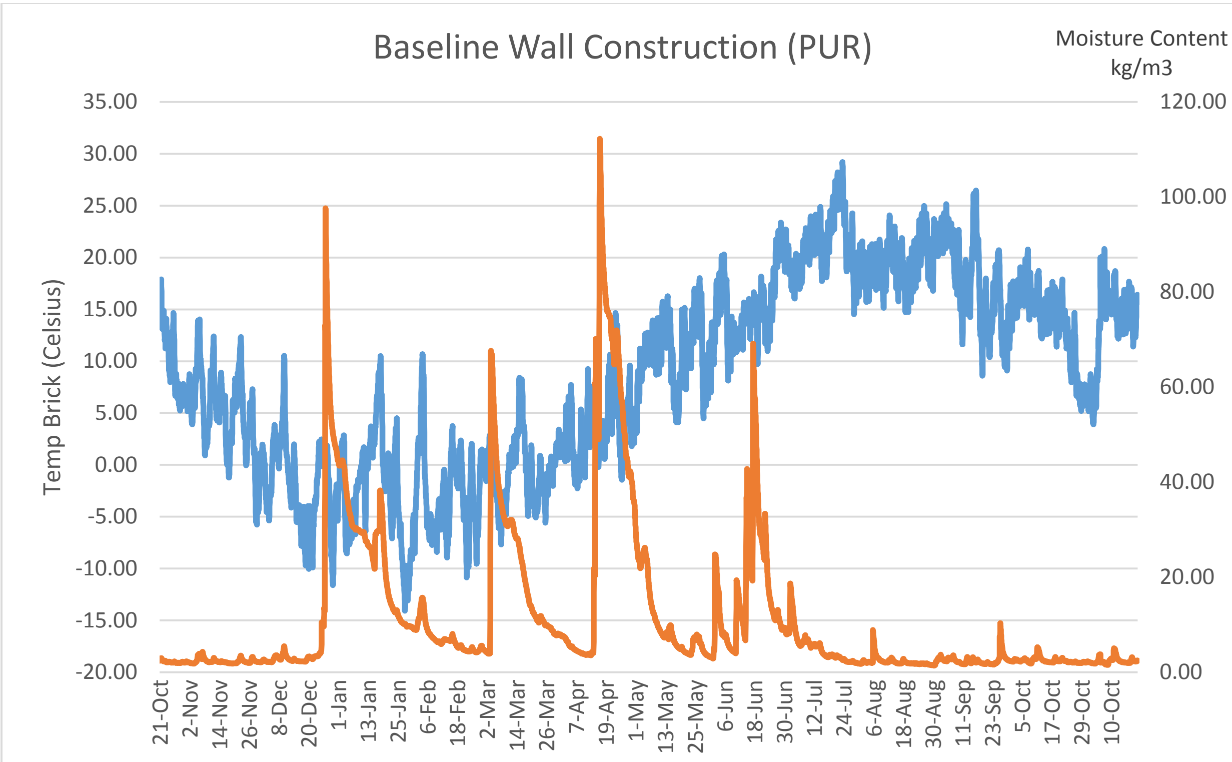
6. Conclusions

Given a known estimated critical saturation point for a pre-world war 2 brick type, does the increase or decrease of interior installed insulation type affect the potential for freeze thaw damage that may occur in the brick masonry structure? Based on the results of the WUFI analysis the answer would be yes. The installed insulation and R value do have an impact on the freeze thaw resistance of the brick masonry. However this relationship is general and not linear. Generally it was observed that the higher the R value of the insulation there was a corresponding lower resistance to freeze thaw damage of the brick masonry. However other factors such as vapour diffusion resistance will impact the critical saturation resistance of the brick masonry. Higher vapour diffusion resistance properties would impede the ability for inward drying of the brick masonry and prolong periods of wetness. The impact of insulation vapour diffusion and its relationship to critical saturation resistance is another potential area of study.

Using thermal resistance and potential for freeze thaw as constraints, what is the optimal level of interior insulation for the particular case study? Given the results of the WUFI analysis all of the insulation options have a low potential for causing freeze thaw damage to the brick masonry wall. In each insulation case the maximum moisture content the brick masonry wall was exposed to (S_{ACT}) at a zero degree crossing was well below the critical saturation limit (S_{CRIT}) as shown in Figure 11 ranging between 62% and 75% freeze thaw resistance. This is predominantly due to the properties of the brick masonry and its ability to hold a relatively large amount of moisture before experiencing freeze thaw damage. The critical saturation of the brick being greater than the free water saturation limit as shown in Table 3 suggests the brick masonry consists of a highly connected pore structure. In most typical weather patterns the brick masonry of the Subject Building would likely not experience critical saturation. This would require additional pressure to force moisture into the brick to exceed a free water saturation state and reach super saturation levels. Therefore the brick masonry in the Subject Building is highly resistant to critical saturation. This is however not the same for all cases and all brick masonry samples. Some brick masonry critical saturation tolerances are much lower. Research work conducted by RDI in collecting a database of critical saturation levels for North American masonry units ranging between the 1830's and 2000's shows that critical saturation levels for bricks are very random. For masonry units with low critical saturation levels the selection of insulation will have a definite impact on the potential for freeze thaw damage to the brick masonry. Since this is not the case for the Subject Building the decision of an optimal interior insulation selection can be informed by what insulation yields the highest R-Value and in this case it is the polyisocyanurate board (PIR) with an insulating value of R7.69.

The method provided shows that when (S_{CRIT}) is known predictive modeling on the impacts of interior insulation on the moisture performance of the brick masonry wall can be used. Further studies should be completed to determine how well the predictive modeling is able to determine actual field performance. Limitations in the model such as being able to incorporate severe weather events and or poor building envelope details that promote atypical levels of moisture accumulation along the brick masonry wall must also be considered. However when all other factors are equal the method of analysis can be an effective tool to use when comparing different interior insulation types and resistance values that can potentially be employed on an interior insulation retrofit renovation project.

Appendix


Baseline Wall Construction (PUR)
Moisture Content
kg/m3
Temp Brick (Celsius)
35.00
30.00
25.00
20.00
15.00
10.00
5.00
0.00
-5.00
-10.00
-15.00
-20.00
120.00
100.00
80.00
60.00
40.00
20.00
0.00
21-Oct
2-Nov
14-Nov
26-Nov
8-Dec
20-Dec
1-Jan
13-Jan
25-Jan
6-Feb
18-Feb
2-Mar
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7-Apr
19-Apr
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13-May
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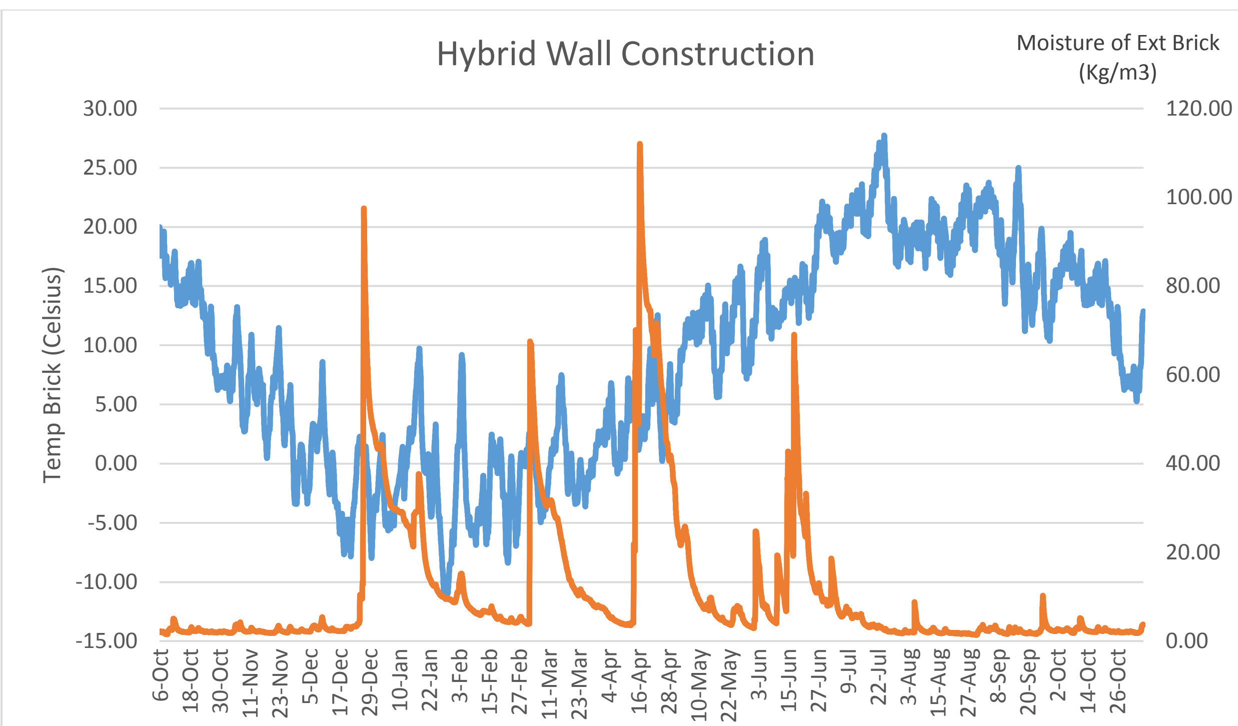
Hybrid Wall Construction
Moisture of Ext Brick
(Kg/m3)
Temp Brick (Celsius)
30.00
25.00
20.00
15.00
10.00
5.00
0.00
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5-Dec
17-Dec
29-Dec
10-Jan
22-Jan
3-Feb
15-Feb
27-Feb
11-Mar
23-Mar
4-Apr
16-Apr
28-Apr
10-May
22-May
3-Jun
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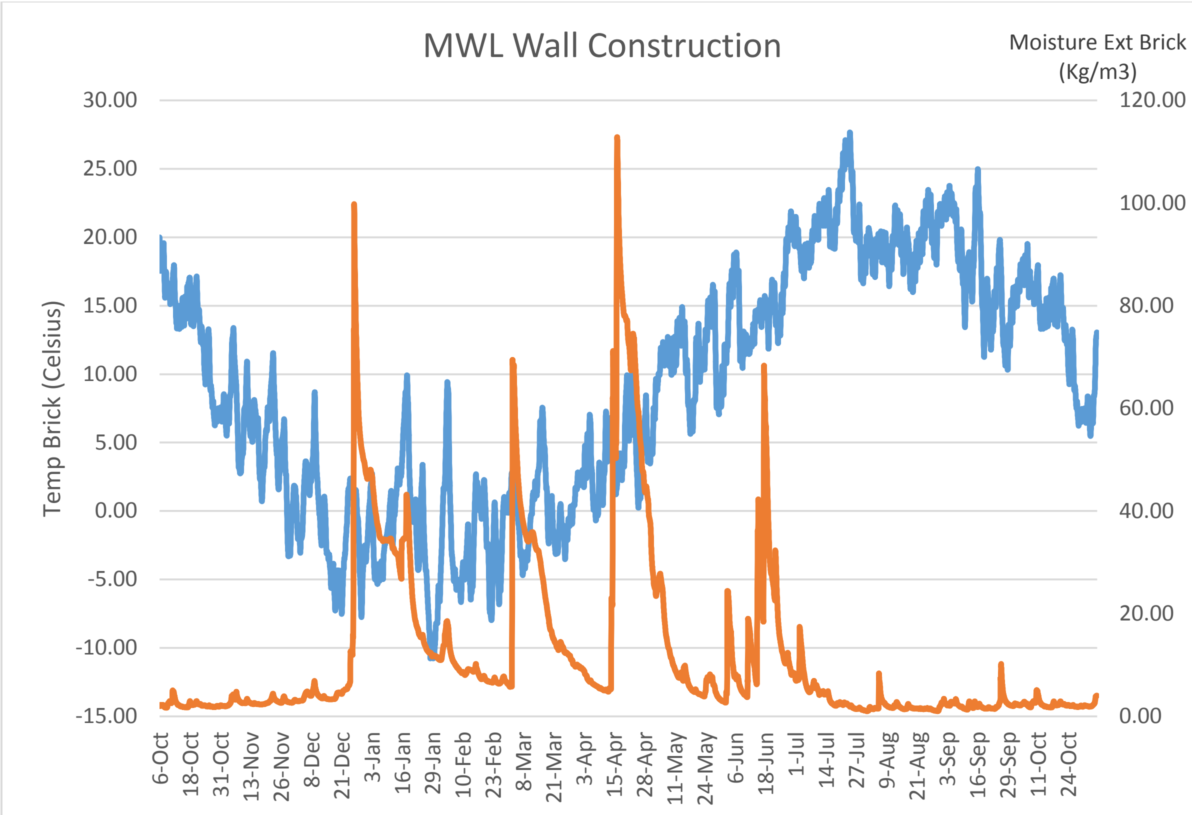
2-Oct
14-Oct
26-Oct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Moisture Ext Brick (Kg/m3)
Temp Brick (Celsius)
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25.00
20.00
15.00
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0.00
-5.00
-10.00
-15.00
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6-Oct
18-Oct
31-Oct
13-Nov
26-Nov
8-Dec
21-Dec
3-Jan
16-Jan
29-Jan
10-Feb
23-Feb
8-Mar
21-Mar
3-Apr
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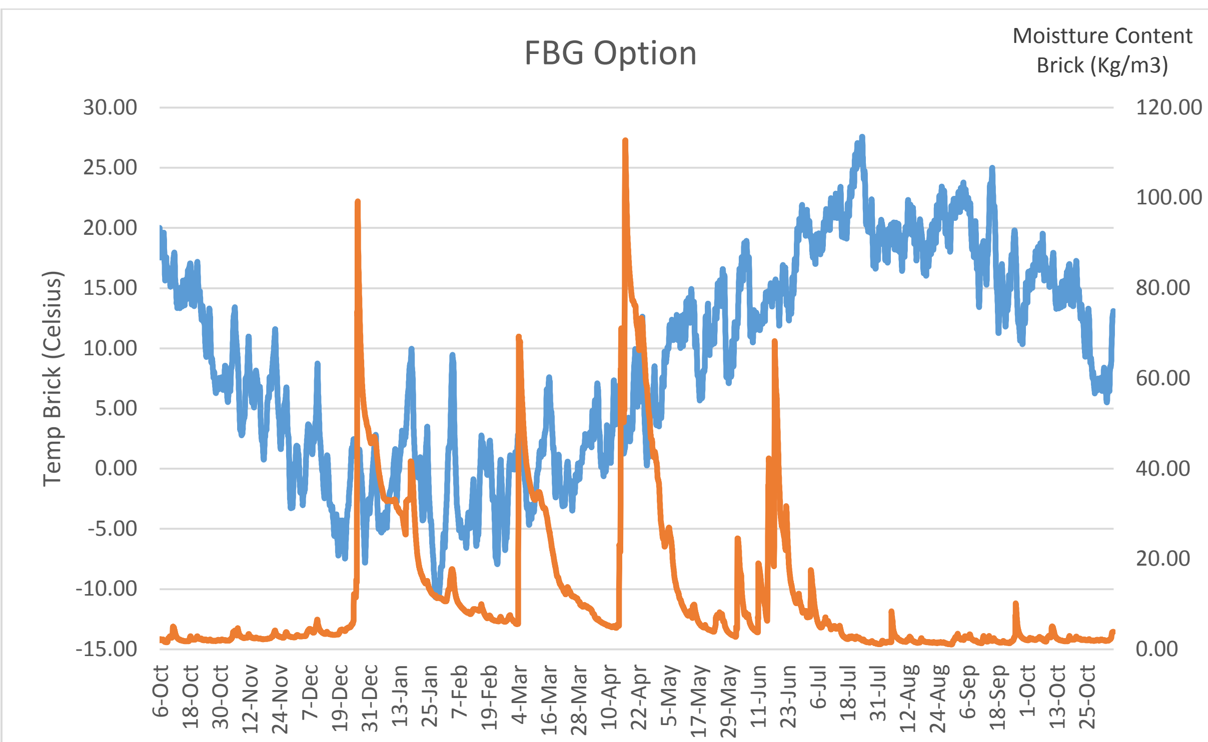
24-Oct


FBG Option
Moistture Content Brick (Kg/m3)
Temp Brick (Celsius)
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20.00
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0.00
-5.00
-10.00
-15.00
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80.00
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6-Oct
18-Oct
30-Oct
12-Nov
24-Nov
7-Dec
19-Dec
31-Dec
13-Jan
25-Jan
7-Feb
19-Feb
4-Mar
16-Mar
28-Mar
10-Apr
22-Apr
5-May
17-May
29-May
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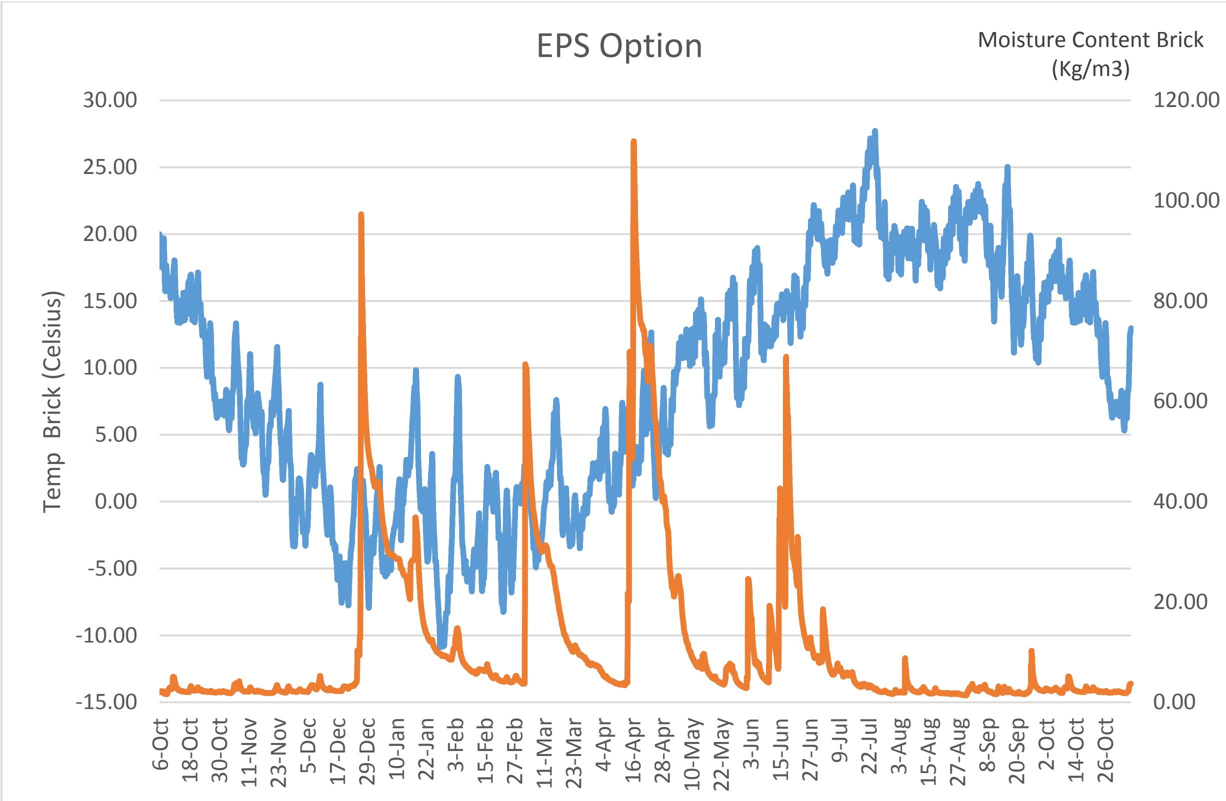
18-Sep
1-Oct
13-Oct
25-Oct


EPS Option
Moisture Content Brick (Kg/m3)
Temp Brick (Celsius)
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25.00
20.00
15.00
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0.00
-5.00
-10.00
-15.00
120.00
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80.00
60.00
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6-Oct
18-Oct
30-Oct
11-Nov
23-Nov
5-Dec
17-Dec
29-Dec
10-Jan
22-Jan
3-Feb
15-Feb
27-Feb
11-Mar
23-Mar
4-Apr
16-Apr
28-Apr
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22-May
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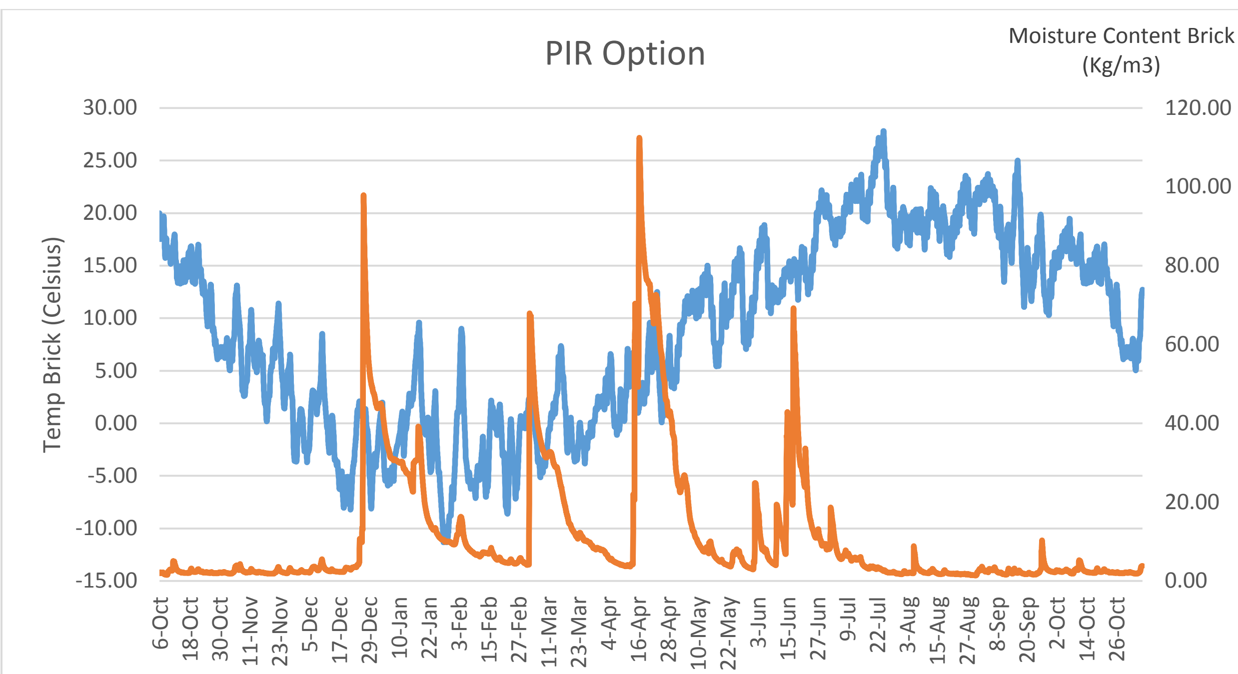
14-Oct
26-Oct


PIR Option
Moisture Content Brick (Kg/m3)
Temp Brick (Celsius)
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-5.00
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6-Oct
18-Oct
30-Oct
11-Nov
23-Nov
5-Dec
17-Dec
29-Dec
10-Jan
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15-Feb
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14-Oct
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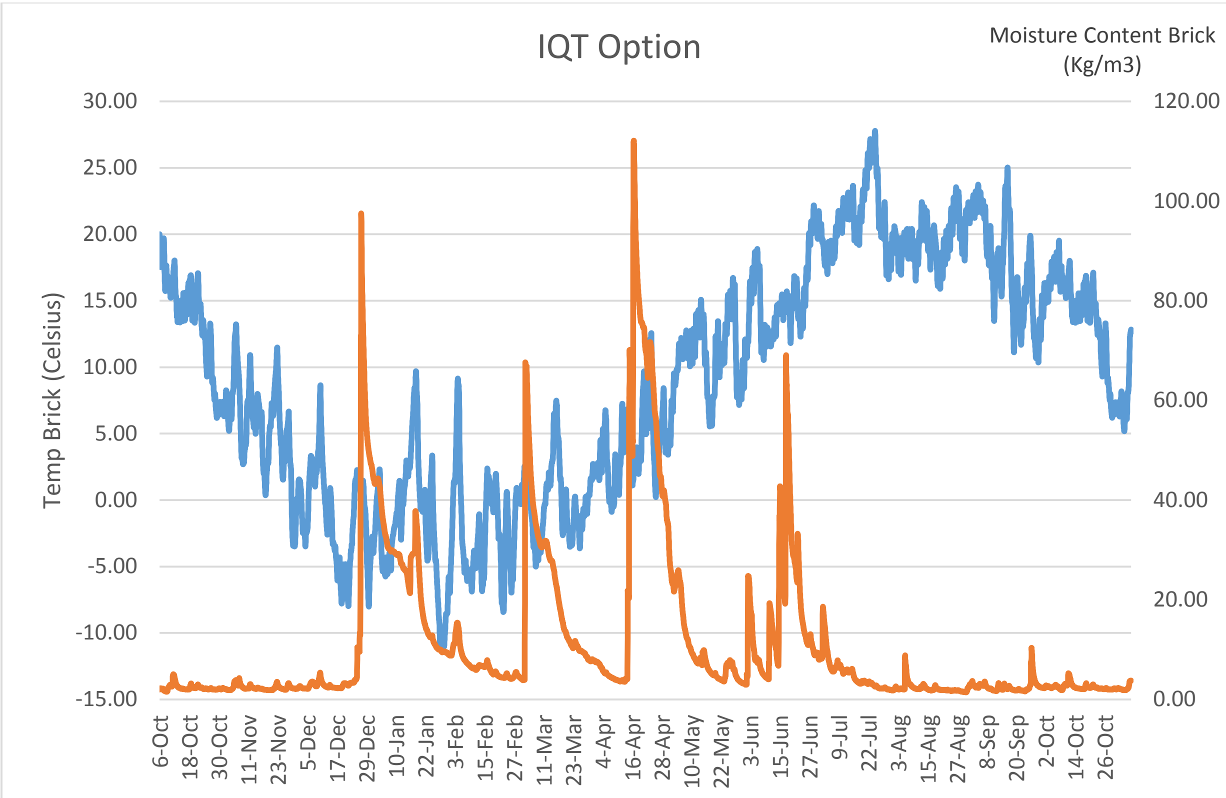
IQT Option
Moisture Content Brick (Kg/m3)
Temp Brick (Celsius)
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11-Mar
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16-Apr
28-Apr
10-May
22-May
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2-Oct
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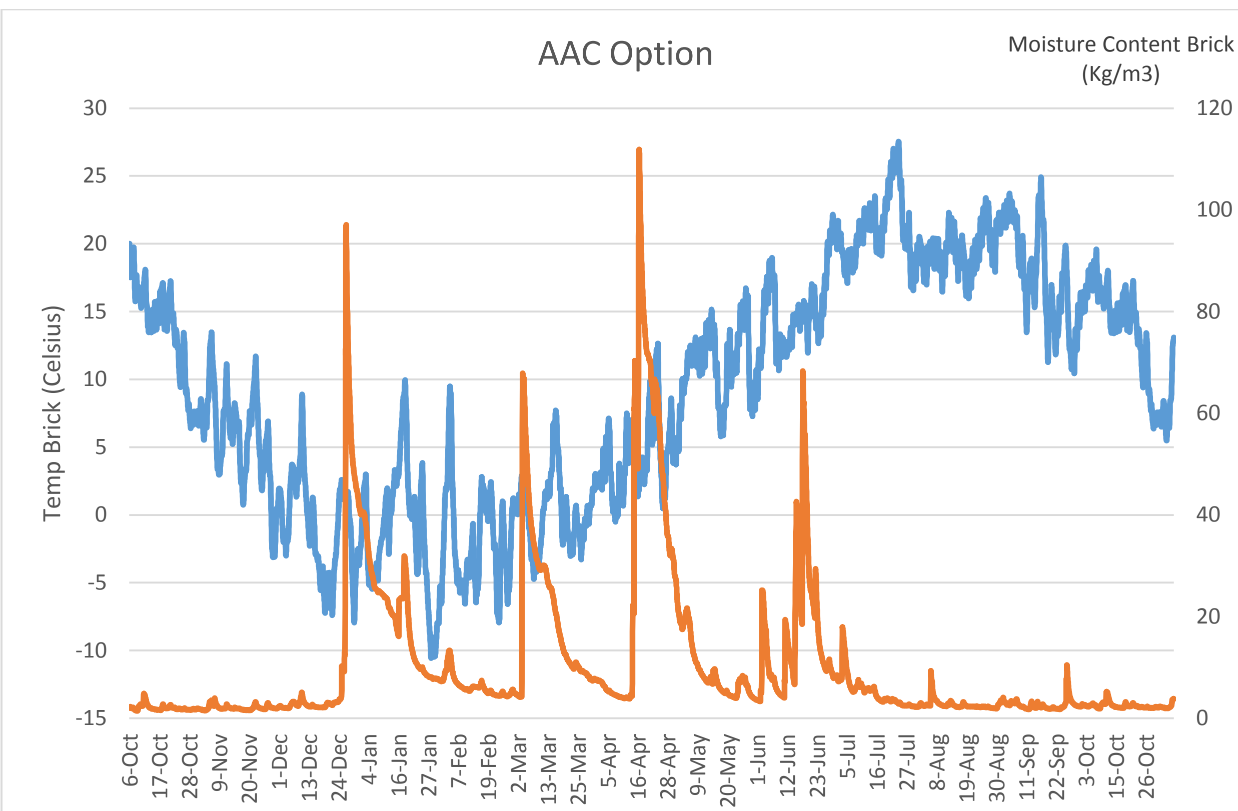
AAC Option
Moisture Content Brick (Kg/m3)
Temp Brick (Celsius)
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25
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15
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0
-5
-10
-15
120
100
80
60
40
20
0
6-Oct
17-Oct
28-Oct
9-Nov
20-Nov
1-Dec
13-Dec
24-Dec
4-Jan
16-Jan
27-Jan
7-Feb
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2-Mar
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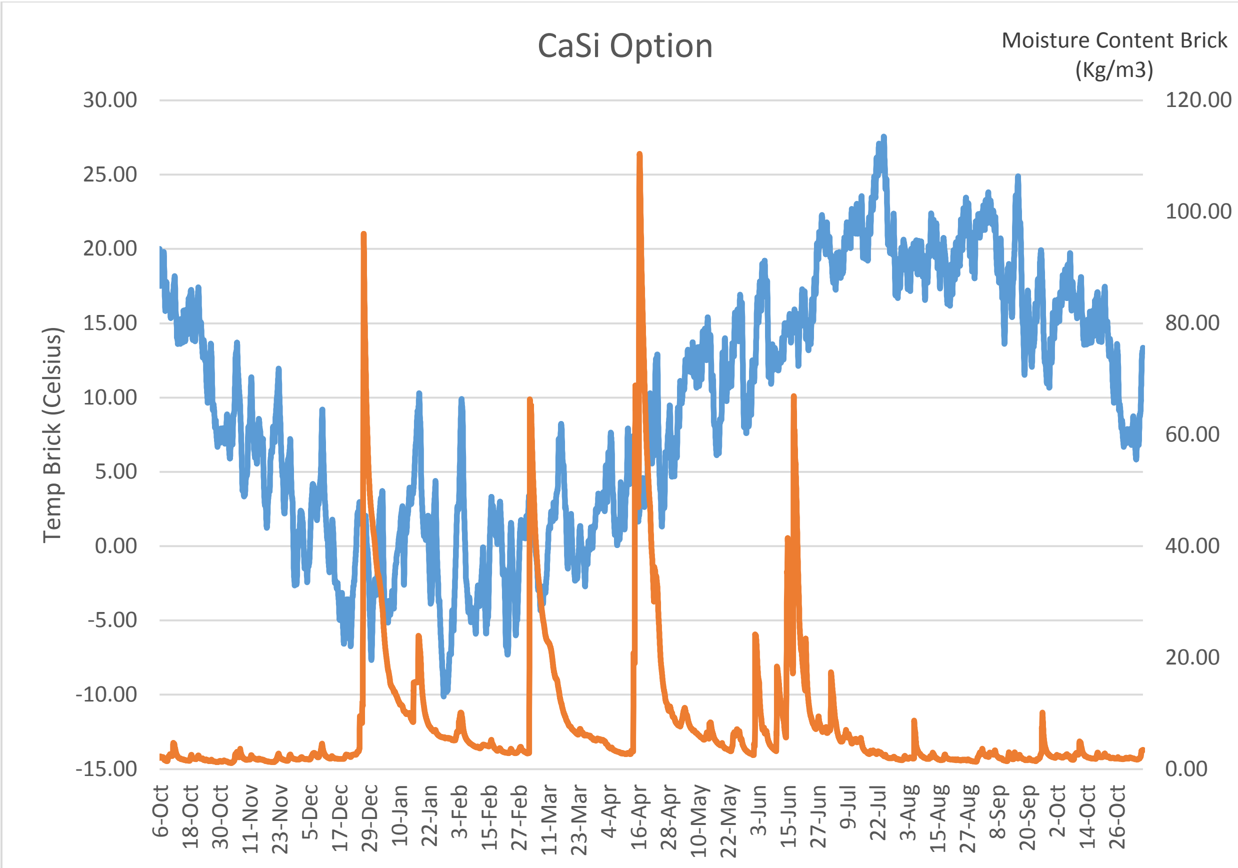
26-Oct


CaSi Option
Moisture Content Brick (Kg/m3)
Temp Brick (Celsius)
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-10.00
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11-Nov
23-Nov
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22-Jan
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11-Mar
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8-Sep
20-Sep
2-Oct
14-Oct
26-Oct

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