High-Performance Brick Mortar Mix to Optimize Moisture Management in Brick Wall

By

Hai Xia
B.Sc., Colorado State University, 2016

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of the Requirements for the Degree of

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in the Department of Mechanical Engineering

Supervisory Committee

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Abstract

The durability of exterior building envelopes is significantly impacted by the presence of water, particularly through the capillary rise mechanism that allows liquid water to penetrate building materials. This process affects both the energy efficiency and durability of buildings. To assess the capillary water intake into porous building materials, the water absorption coefficient is used as a characterization parameter. Additionally, the water vapor permeability of a material indicates its ability to allow moisture to diffuse and escape. In this project, two concentrations of zinc stearate (0.5% w/w and 1% w/w) were added to commonly used mortar. Following the ASTM standard test procedure, the liquid water absorption coefficients and water vapor permeability of brick, mortars, and brick mortar joints were determined. These experimental values were utilized as inputs for the hygrothermal performance analysis (numerical modelling) of the brick wall assembly. The experimental findings suggest that the addition of zinc stearate to the mortar can reduce water absorption capacity while simultaneously enhancing water vapor permeability. Numerical modelling results further demonstrate that the use of high-performance brick mortar materials can significantly improve the moisture management capability for brick walls in the marine-warm and humid climate of Vancouver, BC, Canada.

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1. Introduction

1.1 Background and Motivation

Brick walls have been used for construction for thousands of years, dating back to 7000 BC [1]. In North America, brick walls are widely used because of their durability, long-term lifespan, fire resistance, and excellent thermal mass property [2], etc. They can withstand harsh weather conditions, such as hurricanes, thunderstorms, extreme hot or cold temperatures. Bricks are made to last for generations. The average lifespan of a brick building is estimated at more than 100 years [2]. Brick is a non-combustible material, meaning it does not burn to contribute to the spread of fires. The good thermal mass property means they can absorb and store heat which helps regulating indoor temperature and contribute to energy efficiency of the building by reducing the demand for heating or cooling.

However, brick is a porous material. Brick manufacturers develop the bricks with superior insulation properties in response to environmental regulations and increasing market demand for such solution [26]. The effective method to achieve is by incorporating cavities within the brick’s structure. Additions of materials into the clay during the firing process will lead to the creation of pores. This approach will increase the porosity and decrease the thermal conductivity and density by giving more air contained [26]. Therefore, brick can easily soak up rainwater and absorb moisture, resulting penetrating dampness on the brick wall. Penetrating dampness refers to the movement of moisture from the outer surface of a building’s wall to the interior [3]. This phenomenon typically occurs when external sources of moisture, such as rain driven by strong winds, encounter the building’s wall. The damage may cause mold growth, heat loss, and frost. The mortar used to joint bricks can be vulnerable to water damage as well. Mortar is generally a mixture of sand, cement, and water. When the rain or raindrops strike against the brick wall, it causes splashes and water penetrates the mortar. In summer, the high temperature and heat causes the thermal expansion of bricks and the mortar. In winter, the freezing temperature causes the contraction and shrinkage of bricks and mortar [25]. Besides, the frozen water between the brick mortar joints can expand because ice has less density than water and takes more space, causing the small amounts of mortar chip away. This is identified as mortar spalling. Over the free-thaw cycle, rain or moisture from rising dampness can gradually wear away and deteriorate the mortar [4], causing the mortar joint to crack. Small cracks and holes allow the water to pass through into the wall, collecting and sitting inside. Eventually, the deteriorated mortar may start to detach from the building (Figure1), large sections of the masonry can crumble and fall off (Figure2), posing a risk to the structural stability of the building.

Figure 1. Mortar Deterioration in Fan Tan Alley, Victoria, BC, Canada

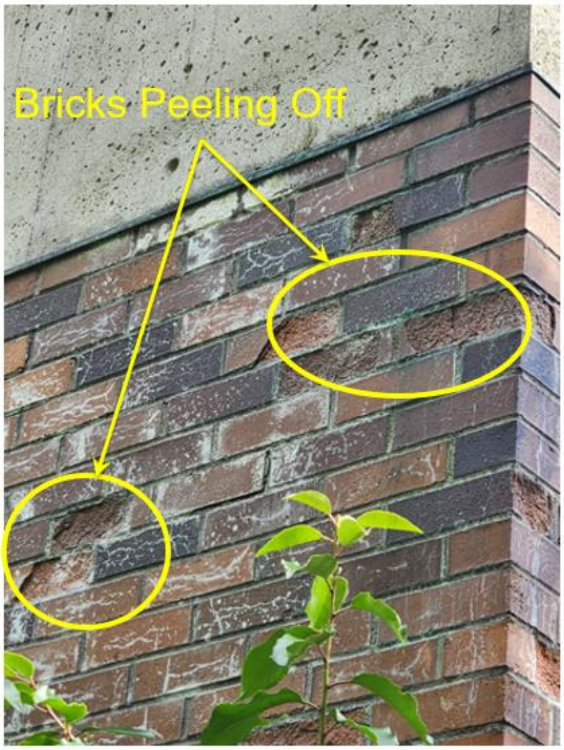


Figure 2. Bricks Peeling off MacLaurin Building in University of Victoria, BC, Canada

The moisture inside which cannot be drained away or dried can develop mold as well, causing a health risk [25]. In Figure 3, the yellow color stuff noticed on the mortar of brick wall is mold growth. This mold is identified as Aspergillus which can trigger allergies, respiratory disease [27].

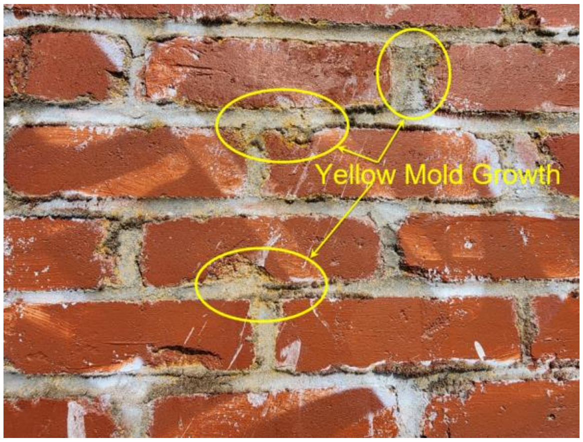


Figure 3. Mold Growth on Brick Wall in Dragon Alley, Victoria, BC, Canada

The coating of white crystalline material on the brick wall is identified as a sign that excess water is present inside, which is called efflorescence [24]. Commonly brick materials contain calcium chloride and sodium salts. In the wintertime, moisture trapped inside the masonry tends to be pushed outward by the heat inside. The natural salts will dissolve as the moisture soaks, after the water evaporates, it will leave the salt behind which is a white crystalline coating mark [24] as shown in Figure 4.

Figure 4. White Crystalline Coating on Brick Wall of Medical Science Building in UVic

In the study [28], the authors showed that the liquid water diffusivity and water vapor permeability are the most important properties which will influence the overall moisture management of the wood-frame stucco wall. In another study [5], the authors indicated that applying the zinc stearate as an admixture with lime-pozzolana plaster can minimum the water liquid diffusivity and maximize the water vapor permeability for exterior stucco cladding. This study is designed to investigate the moisture management performance in brick wall assembly with adding 0.5% w/w zinc stearate and 1% w/w zinc stearate to the mortar mixture.

1.2 Objectives

The research project has two primary objectives:

1) To develop or engineer a high-performance mortar material jointed to the clay brick that restricts the penetration of liquid water through its external surface while enabling water vapor diffusion.
2) To demonstrate and prove that engineered high-performance mortar can improve the moisture management capability of brick walls through numerical modelling exercises.

2. Materials and Methods

2.1 Material Selection

2.1.1 Brick

The five most common types of bricks are used in construction, as shown in Figure 5, including common burnt clay bricks, sand lime bricks, engineering bricks, concrete bricks, and fly ash clay bricks.

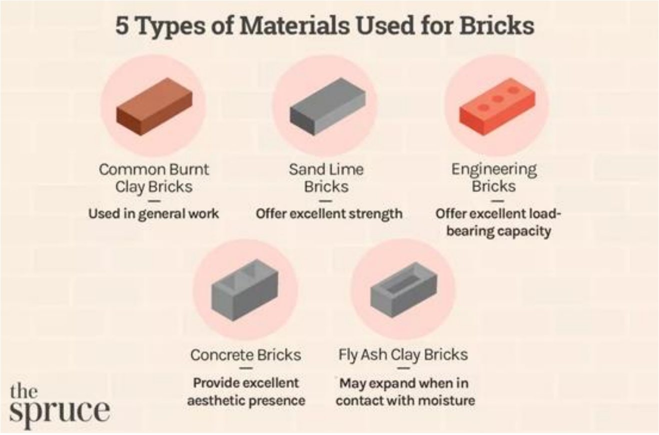


Figure 5. Five Types of Materials Used for Bricks [8]

Sand lime bricks are a mix of sand and lime. They are strong with high compressive strength and are used chiefly for load-bearing wall constructions. Engineering bricks have high compressive strength and excellent load-bearing capacity as well. Besides, they can absorb a large amount of moisture, which makes them usually for basements, manholes, sewers, and retaining walls. Concrete bricks are made from cement, sand, and water. Manufacturers are allowed to build various shapes and sizes. They are typically used to build fences and facades or internal brickwork. Fly ash bricks are a product of coal combustion in power plants, which may encompass hazardous substances such as arsenic, mercury, and chromium. They can be used for foundations, pillars, and structural walls [9].

Burnt clay bricks have been used in buildings worldwide for a long time. They are still the most popular type of bricks in construction. They are made by pressing wet clay into molds, then drying and firing in kilns [8]. They are reddish and can be used in masonry walls, foundations, and columns of buildings. The bricks are plastered with mortar to improve the strength, water resistance, and insulation when building walls.

The clay bricks used in this project are purchased from BROCKWHITE Construction Materials [10] with a standard solid size of 7-1/2″ x 3-1/2″ x 2-1/2″.

2.1.2 Mortar Mixture

Mortar is the essential component that joints bricks or other masonry units, imparting structural strength to walls or other structures. The four main types of mortar mix are type M, type S, type N, and type O [11]. Each mortar type is mixed with a different cement, lime, and sand ratio for specific purposes, bonding properties, and compressive strength.

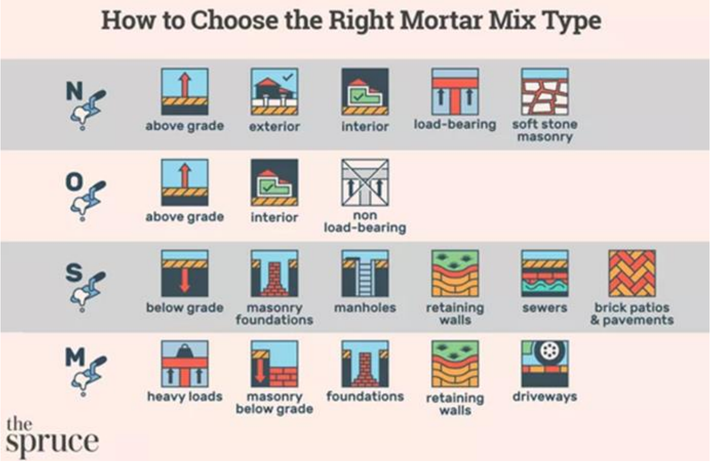


Figure 6. Four Main Types of Mortar [11]

As shown in Figure 6, type M mortar mix has the highest compressive strength with at least 2500 psi and is used mainly for heavy loads and below-grade applications. Type S mortar mix has a compressive strength of over 1800 psi and is the most common choice for below-grade applications, such as masonry foundations, manholes, training walls, servers, and brick patios. Type O mortar mix has a low compressive strength of about 350 psi and is commonly used for above-grade and interior applications. Type N mortar has a medium compressive strength of over 750 psi and is used for above-grade, exterior, and interior load-bearing applications. It is the most used mortar by constructors for building walls. Most type N mortar is mixed with cement, lime, and sand. The lime prevents crack formations due to thermal expansion and contraction. The lime can also improve water vapor permeability to reduce the risk of frost damage due to saturation [12].

This project aims to discover how different concentrations of zinc stearate added to the mortar can decrease water absorption and increase water permeability. Therefore, a type N mortar mixture from SAKRETE [13] preblended mixture of sand and masonry cement without lime, was selected. It has a strength of over 750psi and meets the requirements of ASTM C1714 [14] and ASTM C270 [15]. The mortar mixture requires mixing with water by a ratio of 3.8L water per 25kg mortar instructed by the manufacturer.

2.1.3 Zinc Stearate (ZnS)

Zinc Stearate (ZnS) is a white powder that repels water and emits a mild scent. This substance is insoluble in water, ethyl alcohol, and diethyl ether [16]. However, it is solvable in acids. The molecular formula is $C_{36}H_{70}O_4Zn$. Zinc Stearate prolongs the durability of adobe bricks and plasters, while using zinc stearate makes the adobe surface extremely difficult to wet and resist rainwater [17]. The zinc stearate used in this project was purchased through n2o3.com [18].

2.2 Test Methodology

2.2.1 Liquid Water Absorption

Liquid water diffusivity is the characteristic that determines the water movement rate within a substance triggered by a gradient in water concentration [5]. If a material permits the diffusion of liquid water through its surface, the weight will change over time when it comes to contact with liquid water. A schematic [6] of a suitable testing apparatus is shown in Figure 7, and the increase in weight of the test specimen versus the square root of time indicates that the specimen weight increases linearly before it reaches the saturation limit (Figure8) [6].

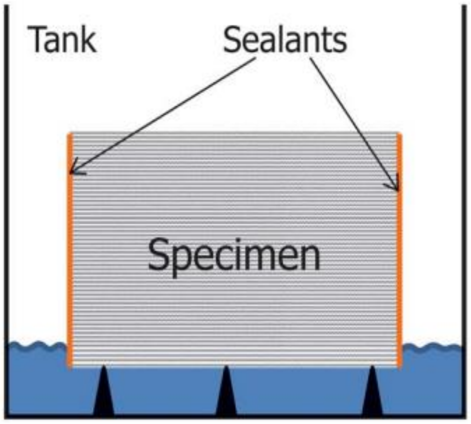


Figure 7. Example of a Suitable Testing Apparatus [6]

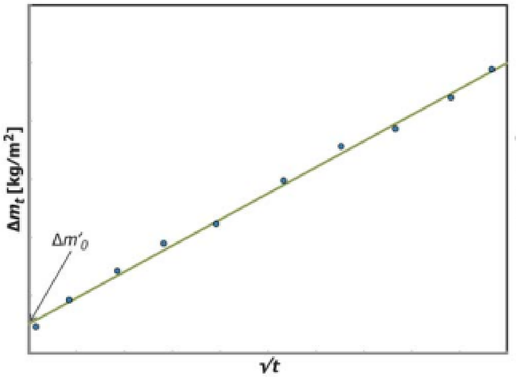


Figure 8. Results from Water Absorption Test [6]

The water absorption coefficient is defined as the mass of water absorbed by a test specimen per surface area and per square root of time. The slope of the linear variation in Figure 8 is the water absorption coefficient (A_w) which can be mathematically written as:

$$\Delta m_t = \frac{m_t - m_i}{A} \tag{1}$$

$$A_w = \frac{\Delta m'_{tf} - \Delta m'_0}{\sqrt{t_f}} \tag{2}$$

Where:

Δm_t = Difference between the area-related mass at each weighing in kg

m_t = Weight of the specimen after time ‘t’ in seconds

m_i = Initial mass of the specimen in kg

A = Liquid contact area of the specimen in m^2

A_w = Water absorption coefficient in $kg \cdot m^{-2} \cdot s^{-1/2}$

$\Delta m'_{tf}$ = Value of Δm on the regression curve at time t_f in kg/m^2

$\Delta m'_0$ = Value of Δm extended by the regression curve to the vertical axes in kg/m^2

In this study, the water absorption coefficient was taken as a measurement of the rate of water movement within a material by the ASTM C1794 - 19 [6], a Standard Test Method for the Determination of the Water Absorption Coefficient by Partial Immersion.

2.2.2 Water Vapor Permeability

Water vapor permeability is defined as the time rate of water vapor transmission through a unit area of flat material of unit thickness induced by the unit vapor pressure difference between two specific surfaces under specified temperature and humidity conditions [5]. The water vapor permeance of a material can be calculated at a given thickness. The experiments are usually performed under isothermal conditions. A test specimen of a given area and thickness separates two environments that differ in relative humidity (RH)/ vapor pressure [5] (Figure9).

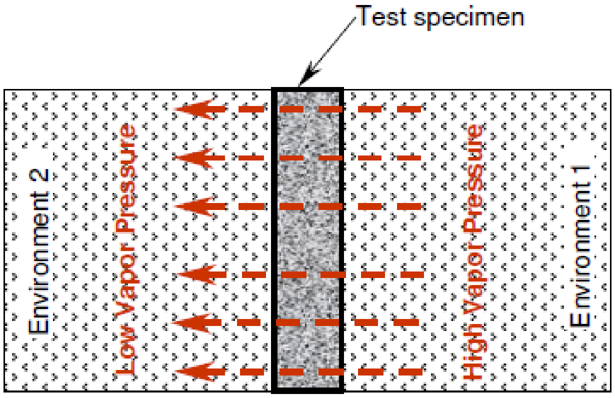


Figure 9. Schematic of Water Pressure Transmission across a Specimen [5]

The steady portion of the test is identified graphically [7], where a straight line adequately fits the plot of at least six properly spaced points (Figure10).

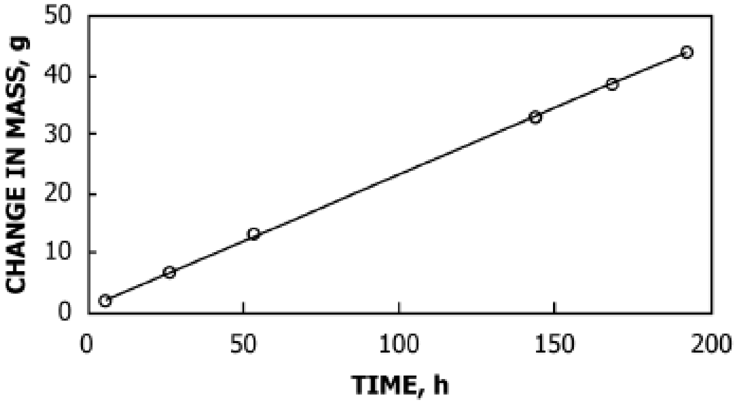


Figure 10. Steady State of Water Vapor Permeability Test [7]

The water vapor permeability of the material is calculated as:

$$WVTR = \frac{G}{t \cdot A} = \frac{G/t}{A} \tag{3}$$

$$WVP = \frac{WVTR}{\Delta p} = \frac{WVTR}{S \cdot (R_1 - R_2)} \tag{4}$$

$$Permeanbility = WVP \cdot thickness \tag{5}$$

Where:

WVTR = rate of water vapor transmission, $g/h \cdot m^2$

G = steady state weight change (from the straight line), g

T = time, h

G/t = slope of the straight line, g/h

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

WVP = water vapor permeance, $kg/m^2 \cdot s \cdot Pa$

Δ_p = vapor pressure difference, Pa

S = saturation vapor pressure at test temperature, Pa

R_1 = relative humidity at the source expressed as a fraction (the test chamber for the desiccant method, in the dish for the water method)

R_2 = relative humidity at the vapor sink expressed as a fraction

2.3 Experimental Work

The experimental work was undertaken in three phases for liquid water diffusivity: **Phase I** – Preparation and testing of base brick and base mortar, **Phase II** – Preparation and testing of brick jointed with base mortar, and **Phase III** – Preparation and testing of brick jointed with modified mortar, and modified mortar alone for high performance.

The objective of *phase 1* was to establish the base liquid water absorption coefficient and water vapor permeability of commonly used clay brick and base mortar. The objective of *phase 2* was to establish the liquid water absorption coefficient of clay brick jointed with base mortar, which allowed to establish the jointed performance and water absorbed in the jointed face between brick and mortar. The objective of *phase 3* was to develop a modified brick jointed with different concentrations of zinc stearate mixed in the mortar, which has a lower liquid water absorption coefficient but higher water vapor permeability than the brick jointed with base mortar.

2.3.1 Liquid Water Absorption

Base brick, brick jointed with base mortar, brick jointed with 0.5% zinc stearate mortar, brick jointed with 1% zinc stearate mortar, base mortar, 0.5% zinc stearate mortar, and 1% zinc stearate mortar were tested for water absorption test. The following apparatus, test specimen, and procedure follow the guidance of ASTM C1794 – 19 [6] and ASTM C1403 – 22a [19].

Apparatus

The apparatus must contain the following for the experimental work:

1. A scale to measure the specimen’s weight with accuracy within ±0.1% of the specimen’s mass.
2. A water tank with a regulation system (Figure11) to keep the water level constant within ±3 mm (±1/8 in.) and equipment to keep the position of the specimen at least 5 mm (1/4 in.) above the bottom of the tank without harming the specimen.
3. Equipment to measure the time with at least 1-second accuracy.

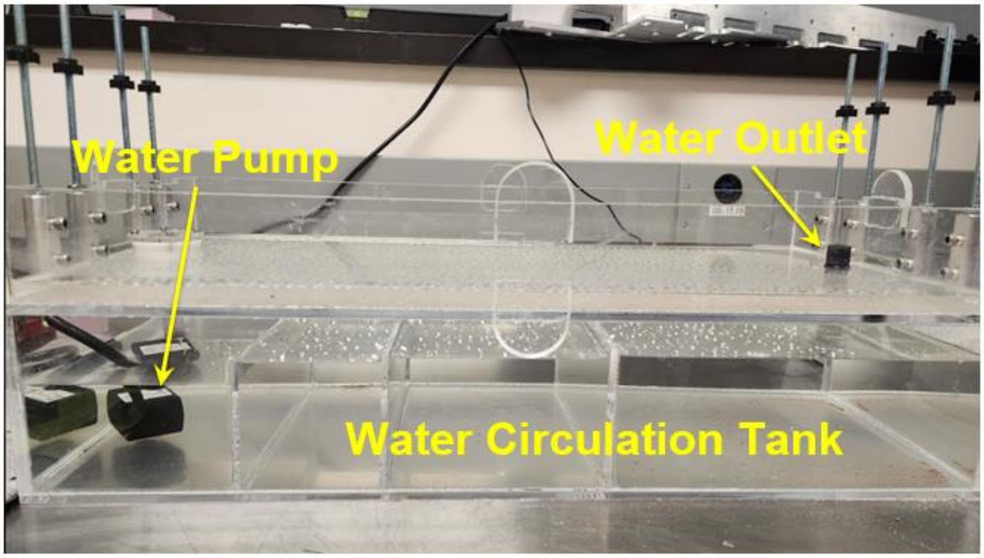


Figure 11. Circulation Water Tank for Water Absorption Test

Test Specimen

At least three specimens shall be tested if the water contact area is greater than $100cm^2$ ($16\ in^2$). At least six specimens shall be tested if the water contact area is less than $100cm^2$ ($16\ in^2$). This experimental work prepared three specimens of base brick, brick jointed with base mortar, brick jointed with 0.5% zinc stearate mortar, and brick jointed with 1% zinc stearate mortar. Six specimens of base mortar, 0.5% zinc stearate mortar, and 1% zinc stearate mortar were prepared while the water contact surface area of mortar specimens is less than $100cm^2$. All test specimens were cured for at least 7 days before next processing. Base brick specimen size was 190x64x89 mm. Brick jointed with mortar specimen size was 202x64x89mm. Mortar specimen was prepared in silicone soap molds, the size was 80x25x50mm.

The cured specimens were put in the oven before coating for drying at 110 ± 5ºC for no less than 24 hours and until two successive weighing at intervals of 2h showed an increment of loss not greater than 0.2% of the last determined weight of the specimen.

As requested by the ASTM C1794-19, all four sides of the test specimens except the top and bottom surfaces shall be sealed with water and vapor-tight sealant that does not react chemically with or significantly penetrate the pores of the specimen. The sealant was mixed with beeswax and rosin with a ratio of 1:1 [7], melted with a wax heater, and brushed onto the specimen's surfaces (Figure12). The total thickness is the sum of the beeswax coating and the substrate.

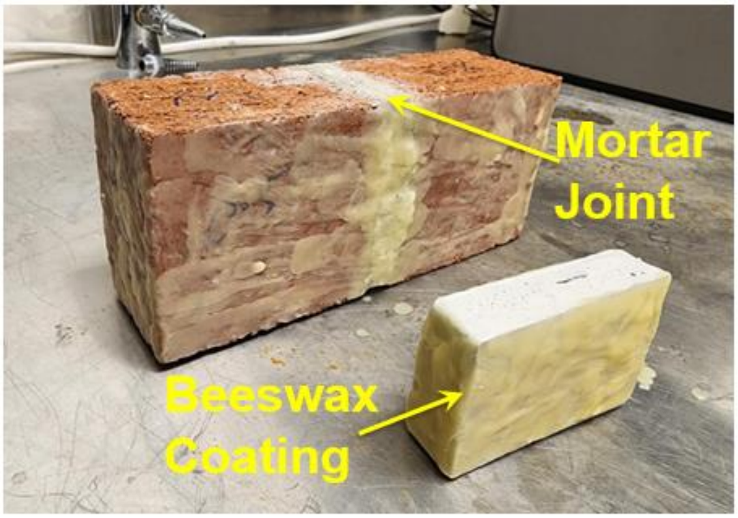


Figure 12. Finished Beeswax Coating of Mortar and Brick Jointed with Mortar

Procedure

1. The procedure must be conducted within the conditions stated in table1.

Table 1 – Test Conditions for Water Absorption Test [6]

	Temperature
Allowed a range of test conditions	20 to 24ºC (64 to 73ºF)
Allowed variation during the test	± 2ºC (± 4ºF)

2. Weigh and record each specimen at steady state with an accuracy of ±0.1% of mass to determine the initial mass.
3. The circulation tank is filled with water to the specific level and ensure a distance between the specimen and the tank bottom of at least 5mm (1/4 in.). Wait until the water temperature reaches the same room temperature as test specimens.
4. Put the stand into the tank and set the test specimen on the stand. The water level shall be kept at a constant 5 ± 2.5mm (0.2 ± 0.1 in.) above the absorbing surface of the specimen.
5. Start the time measurement precisely when the specimen first contacts the liquid water.
6. After approximately 5 min, 30min, 1h, 2h, 4 h, 8 h, 24 h, remove the specimen from the water and using a moist sponge to remove water drops. Weigh the specimen and put the specimen immediately back into the water.
7. If liquid water shows up on the top surface of the specimen, the measurement shall be terminated.

8. If the liquid water uptake is less than 0.001 kg/m^2 (0.0002 lb/ft^2) of the absorbing surface, the measurement can be terminated, and the material can be determined as water resistance.
9. After termination of the measurement, the specimen shall be investigated for cracking of the sealant.

Figure 13, Figure 14, and Figure 15 show the water absorption test for mortar, brick, and brick jointed with mortar. Mortar specimens used one stand and brick specimens used two stands as support for each specimen.

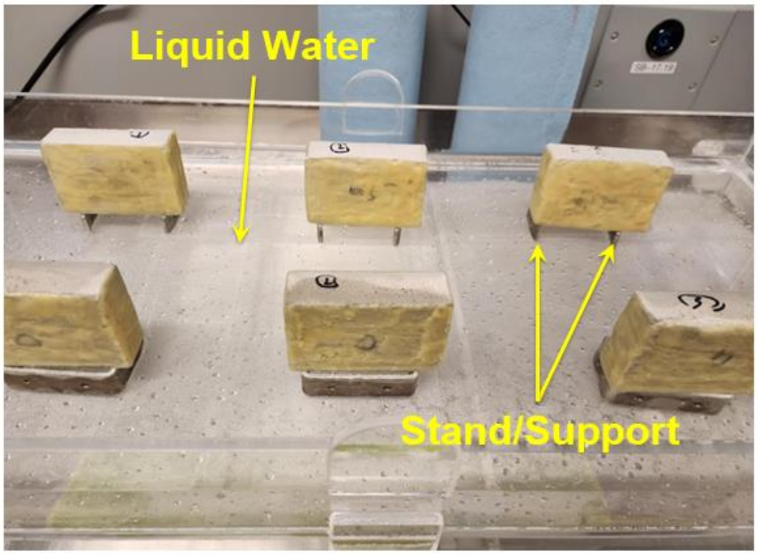


Figure 13. Mortar Water Absorption Test

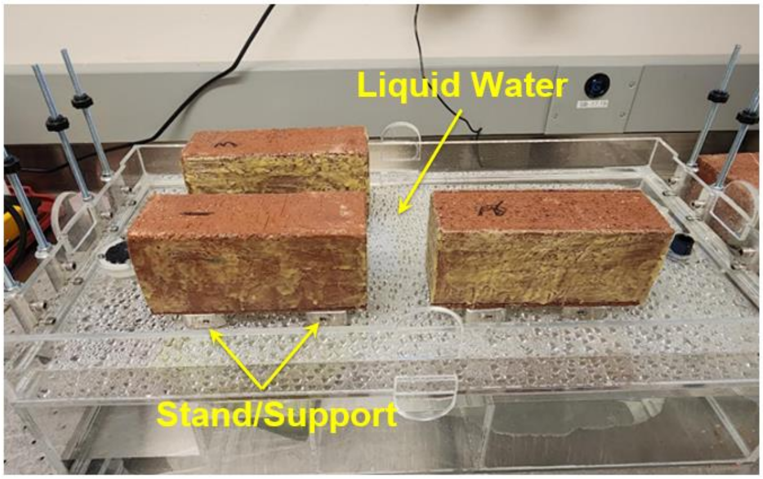


Figure 14. Brick Water Absorption Test

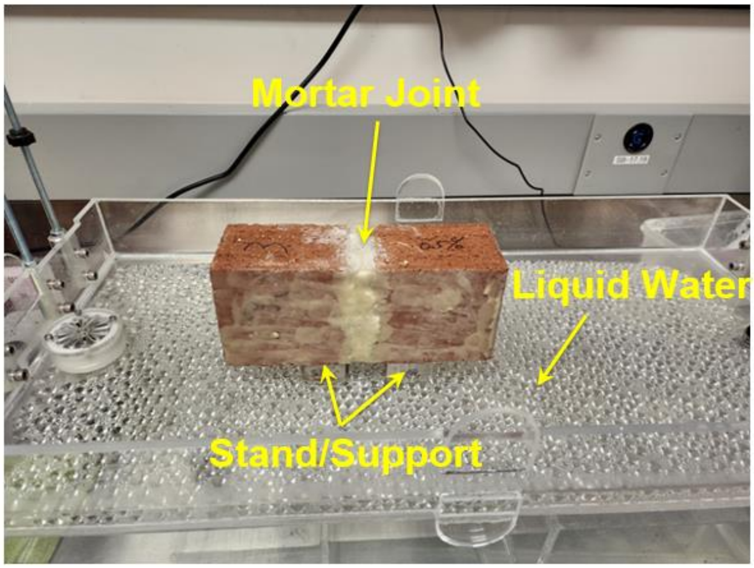


Figure 15. Brick Jointed with Mortar Water Absorption Test

2.3.2 Water Vapor Permeability

Base brick, base mortar, 0.5% zinc stearate mortar, and 1% zinc stearate mortar were tested for water vapor permeability with dry cup and wet cup test method. The following apparatus, test specimen, and procedure follow the guidance of ASTM E96/E96M – 22a [7].

Apparatus

The apparatus must contain the following for the experimental work:

1. Test dish shall be of any noncorroding material which is impermeable to water or water vapor. The mouth of the dish shall be at least 3000 mm^2 [4.65$in.^2$] in area.
2. The cabinet for the test dishes is to be placed shall have a controlled temperature and relative humidity. Temperature shall be maintained at ± 2.8 ºC [5 ºF] at a given measurement point, with the average at the end of the test period being within ± 1.1 ºC [2 ºF] of the specified test condition. Relative humidity shall be maintained at ± 5 % at a given measurement point, with the average at the end of the test period being within ± 2% of the specified test condition.
3. Weighing shall be performed using an electronic analytical balance of suitable capability. The balance shall have enough capacity to accommodate the assembled dish mass and, in the case of desiccant method testes, added mass of any moisture gained.

4. For the desiccant method, anhydrous calcium chloride in the form of small pellets what will pass a No. 8 [2.36-mm] sieve and free of fines that will pass a No.40 [600-µm] sieve shall he used. Desiccant to be reused shall be dried at 200ºC [400ºF] for 4 hours per inch of desiccant depth in vessel. Redried desiccant shall be stored in a sealed contained and be at room temperature before use.
5. For the water method, distilled water shall be used in test dish.
6. The sealant used for attaching the specimen to the dish must be impervious to the passage of water vapor and water.

Test Specimen

At least three specimens shall be tested by the same method within the vapor flow in the designated direction. Materials of homogeneous composition and physical structure shall be test at any thickness to determine water vapor permeance. When determining permeability, the spacemen musty be a minimum of 12.5mm (1/2 in.) thick. All tests require an additional blank specimen to be tested exactly like others, except that no desiccant or water is put in the dish. The time to reach equilibrium of water vapor transmission increases as the square of the thickness. The blank specimen is used to cancel out the effects of barometric pressure changes eliminating the need for buoyancy corrections, moisture changes of hygroscopic materials, and mass change of uncured specimens. This enables more accurate calculations and reduces the time to establish steady state mass change. The blank specimen becomes the fourth specimen of a standard three dish test set.

As requested by the ASTM C1794-19, all sides of the test specimens except the top and bottom surfaces shall be sealed with water and vapor-tight sealant that does not react chemically with or significantly penetrate the pores of the specimen. The sealant is mixed with beeswax and rosin with a ratio of 1:1 [7], melted with a wax heater, and brushed onto the specimen's surfaces. The total thickness is the sum of the beeswax coating and the substrate. The brick is put on the food container with precut test area on the lid. All edges between the brick and lid are sealed with beeswax coating (Figure16). Brick specimen was cut into a 25.4mm (1in.) thickness for testing. Mortar Specimen was prepared in silicone round cake mold (Figure17). The finished size is 76.2mm in radius and 18mm in thickness. Specimen was cured for 7 days and put in the oven before coating for drying at 110 ± 5ºC for no less than 24 hours and until two successive weighing at intervals of 2 hours showed an increment of loss not greater than 0.2% of the last determined weight of the specimen.

The mortar has a slight larger size than test dish, any excessive top surface area of the mortar is covered by beeswax coating. The edges between mortar and test dish are covered and sealed by beeswax coating as well (Figure18).

Figure 16. Brick Specimen for Water Vapor Permeability Test

Figure 17. Mortar Specimen Preparation for Water Vapor Permeability Test

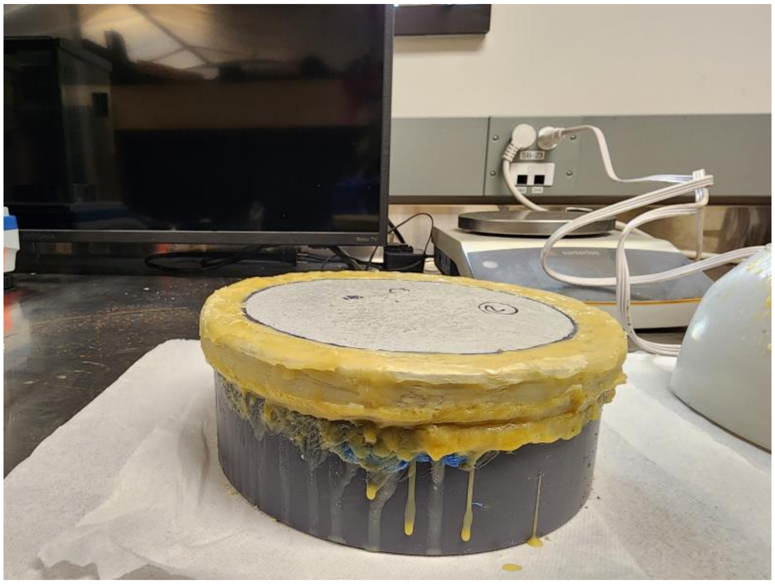


Figure 18. Mortar Specimen Coating with Test Dish

Procedure for Desiccant Method (dry cup)

1. The test dish is filled with desiccant within 6mm (1/4in.) of the specimen. Weigh the amount of desiccant placed in each dish. Leave enough space so that shaking of the dish, to be done at each weighing will mix the desiccant.
2. Attach the specimen to the dish and place it in the controlled environment chamber.
3. Weigh the dish assembly periodically, enough to obtain at least six data points at steady state.
4. Terminate the test or change the desiccant before the water absorbed by the desiccant exceeds 10% of starting weight. The desiccant gain is isolated using the blank specimen to adjust for moisture content change of the specimen.

Procedure for Water Method (Wet cup)

1. The test dish is filled with distilled water to a level 19 ± 6 mm (¾ ± ¼ in.) from the specimen. The air space allowed has a small vapor resistance, but it is necessary to reduce the risk of water touching the specimen when dish is handled.
2. Attach the specimen to the dish and place it in the controlled environment chamber on a horizontal surface.
3. Weigh the dish assembly periodically, enough to obtain at least six data points at steady state.

4. Terminate the test or change the desiccant before the water absorbed by the desiccant exceeds 10% of starting weight. The desiccant gain is isolated using the blank specimen to adjust for moisture content change of the specimen.

2.3.3 Numerical Modelling

After evaluating the water absorption rates and water vapor permeability properties of the brick, and mortar materials, the moisture management or hydrothermal performance of the high-performance brick jointed with mortar is performed using WUFI software.

Based on the results available from the experimental study, the following materials are selected for the numerical study:

1. Brick jointed with 0% zinc stearate mortar
2. Brick jointed with 0.5% zinc stearate mortar
3. Brick jointed with 1% zinc stearate mortar

Inputs for Modelling

There are several major input parameters required for the simulation, such as:

1. Components
    I. Wall Assembly/Monitor Positions
    II. Orientation
    III. Surface Transfer Coefficient
    IV. Initial Conditions
2. Control
    I. Calculation Period/Profiles
    II. Numeric
3. Climate
    I. Outdoor
    II. Indoor

The following sections outline these inputs parameters as applicable for this study.

Wall Construction Details

Figure19 describes the construction details of brick wall considered in this study.

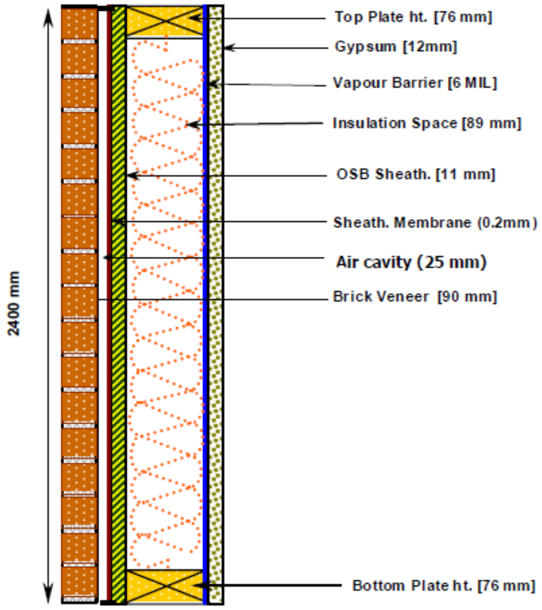


Figure 19. Brick Wall Assembly Details [20]

In the WUFI software database, the following layers are specified and shown in Figure20:

1. The modified brick layer based on Solid Brick Bernhard (0.09m)
2. An air layer (0.025m)
3. ZIP System sheathing (0.0002m)
4. Plywood (USA) (0.011m)
5. Cellulose Fiber Insulation (0.089m)
6. 3M Air and Vapor Barrier 3015 (0.000152m)
7. Gypsum Board (USA) (0.012m)

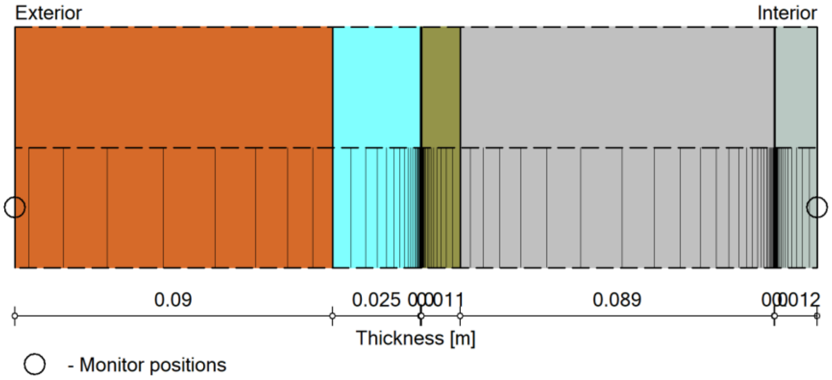


Figure 20. Wall Design In WUFI

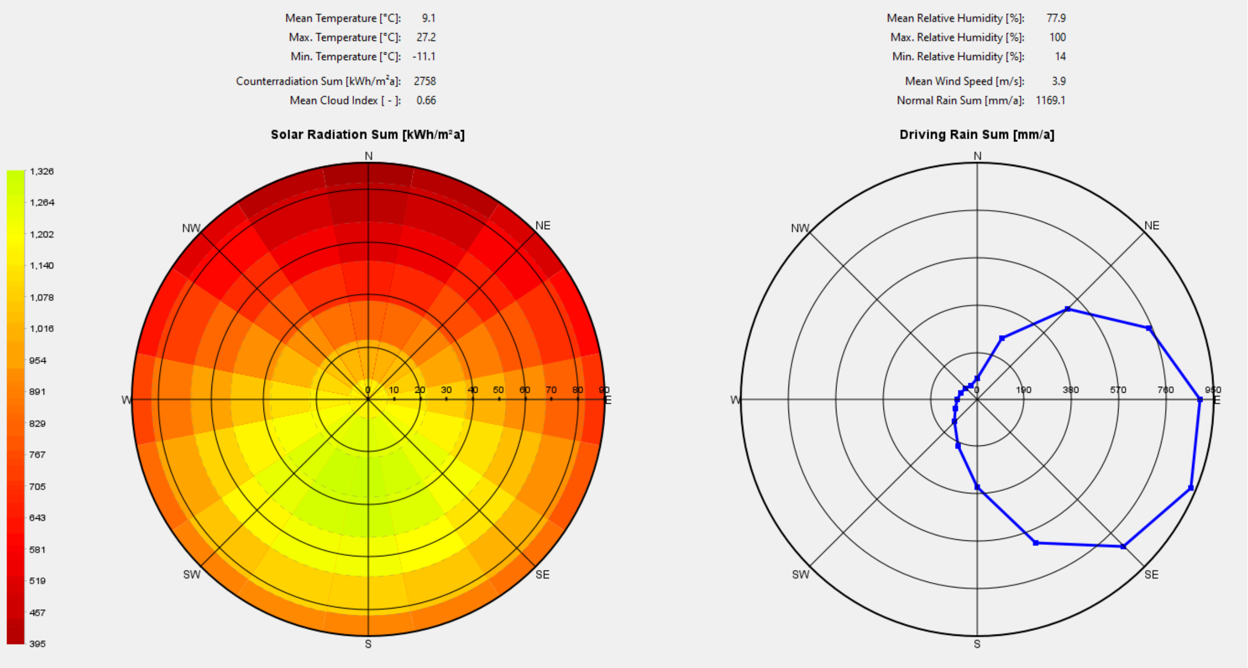
Material Properties

Simulation using WUFI requires seven sets of material properties: Moisture Storage Function, liquid transport coefficient (suction), liquid transport coefficient (redistribution), water vapor diffusion resistance factor (μ), thermal conductivity (moisture dependent), thermal conductivity (temperature dependent, and enthalpy (temperature dependent).

It is noted that the reference water content, free water saturation water content, water absorption coefficient and water vapor diffusion resistance factor are obtained from respective measure values. The other properties of the selected brick material are not changed. The material properties for other components of the brick wall are also taken from the WUFI property database.

Boundary Conditions

The climate selected is Vancouver (Canada) in both cold year and warm year. The orientation is changed to east side due to the study shows the prevailing wind driven rain direction is from the east [21]. The climate analysis of cold and warm year is shown in Figure 21 and 22. Surface transfer coefficient is using the default value. Initial relative humidity and temperature in component are not changed with 0.8 and 20ºC. Three years of simulation is taken staring from 1/1/2023 to 12/31/2025.



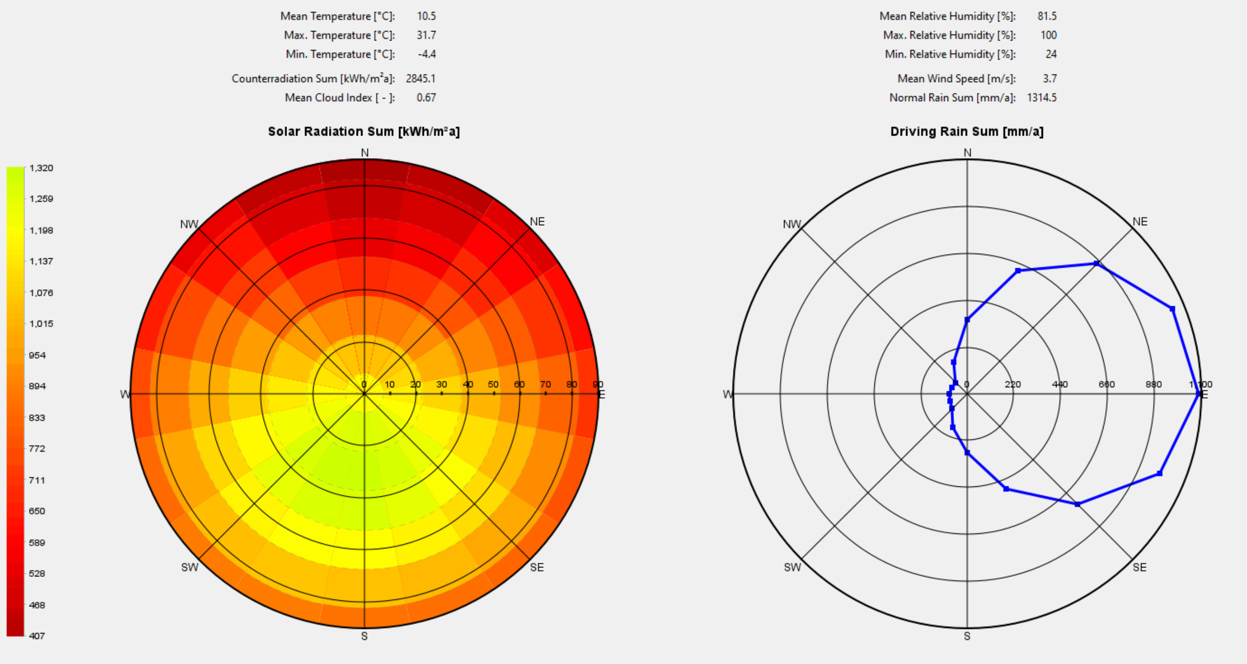
Mean Temperature [°C]: 9.1
Max. Temperature [°C]: 27.2
Min. Temperature [°C]: -11.1
Counterradiation Sum [kWh/m²a]: 2758
Mean Cloud Index [-]: 0.66

Mean Relative Humidity [%]: 77.9
Max. Relative Humidity [%]: 100
Min. Relative Humidity [%]: 14
Mean Wind Speed [m/s]: 3.9
Normal Rain Sum [mm/a]: 1169.1

Solar Radiation Sum [kWh/m²a]

Driving Rain Sum [mm/a]

Figure 21. Climate Analysis of cold year in Vancouver



Mean Temperature [°C]: 10.5
Max. Temperature [°C]: 31.7
Min. Temperature [°C]: -4.4
Counterradiation Sum [kWh/m²a]: 2845.1
Mean Cloud Index [-]: 0.67

Mean Relative Humidity [%]: 81.5
Max. Relative Humidity [%]: 100
Min. Relative Humidity [%]: 24
Mean Wind Speed [m/s]: 3.7
Normal Rain Sum [mm/a]: 1314.5

Figure 22. Climate Analysis of warm year in Vancouver

3. Results and Discussion

3.1 Results of Liquid Water Absorption Test

For the brick and brick jointed mortar with different concentrations of zinc stearate, the water absorbed versus time is shown in Figure 23. All test specimens show a similar trend: a large ramping in the first two hours of the test. The curve smooths down to flat line after 4 hours of the test, indicating the equilibrium state of water absorption. It shows that the base brick absorbs the least water during the test. However, when the brick joins with the base mortar, it absorbs the most amount of water. After mixing with 0.5% w/w zinc stearate to the mortar, the jointed brick mortar has a noticeable water absorption decrease. And brick jointed mortar with a mixing of 1% w/w zinc stearate decreases more water absorbed. The trend shows the water absorption coefficient can be determined by using the first three data points from the test, because it shows the best straight line covering the data points.

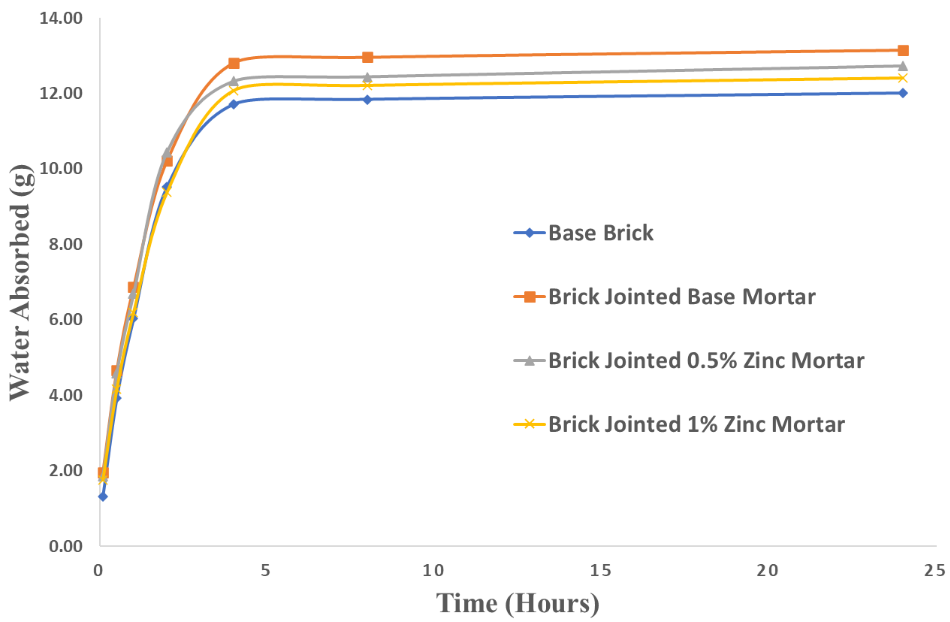


Figure 23. Water Absorbed versus Square Root of Time of Base Brick and Brick Jointed with Different Concentrations of Zinc Stearate Mortar

Figure 24 is the linear curve of average area-related mass difference of test specimens versus square root of time. The first three data points were used for creating the trendline. The slope of the linear lines is the water absorption coefficient. The lines of equations are included in Appendix A.

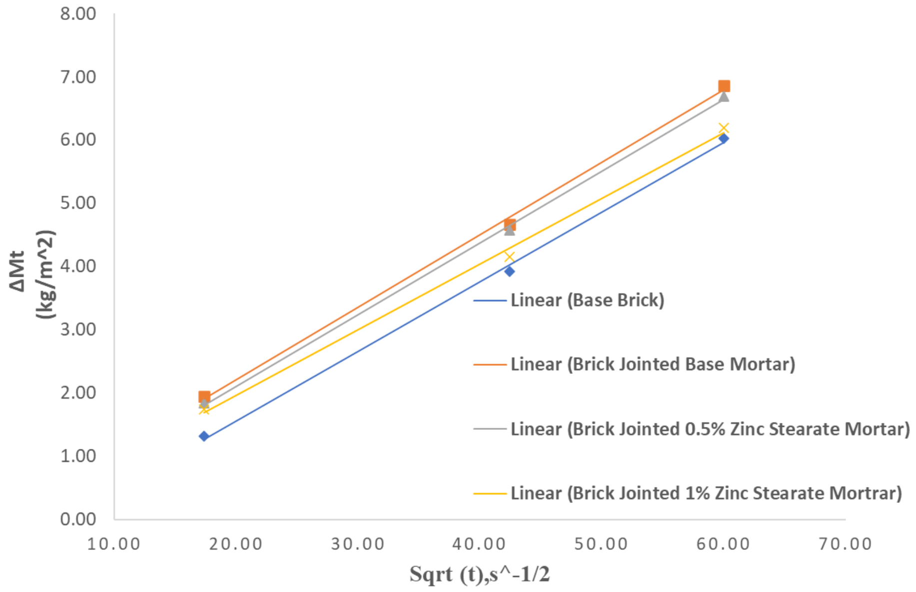


Figure 24. Brick and Brick Mortar Joints Area-related Mass Difference of Test Specimens versus Square Root of Time

Table 2 and Figure 25 show the calculated results of the water absorption coefficient for each specimen. Both bricks jointed with 0.5% zinc stearate mortar and 1% zinc stearate mortar have a decreased water absorption coefficient compared to brick jointed with base mortar.

After jointed with base mortar, the base brick exhibits a slight increase in water absorption coefficient from 0.11 $kg \cdot m^{-2} \cdot s^{-1/2}$ to 0.1146 $kg \cdot m^{-2} \cdot s^{-1/2}$ due to the higher water absorption coefficient of the mortar compared to the brick. However, when the brick is jointed with jointed with 0.5% zinc stearate mortar, the water absorption coefficient decreases to 0.1131 $kg \cdot m^{-2} \cdot s^{-1/2}$, slightly lower than the brick jointed with base mortar. The water absorption coefficient experiences a significant decrease to 0.1036 $kg \cdot m^{-2} \cdot s^{-1/2}$ when the brick is jointed with 1% zinc stearate mortar. The measured density is included in Appendix A.

Table 2 – Average Water Absorption Coefficient of Brick and Brick Jointed with Mortar

Specimen	**Water Absorption Coefficient ($kg \cdot m^{-2} \cdot s^{-1/2}$)**
Normal Brick	0.110 ± 0.0099
Brick Jointed Base Mortar	0.115 ± 0.0185
Brick Jointed 0.5% Zinc Stearate Mortar	0.113 ± 0.0018
Brick Jointed 1% Zinc Stearate Mortar	0.104 ± 0.0085

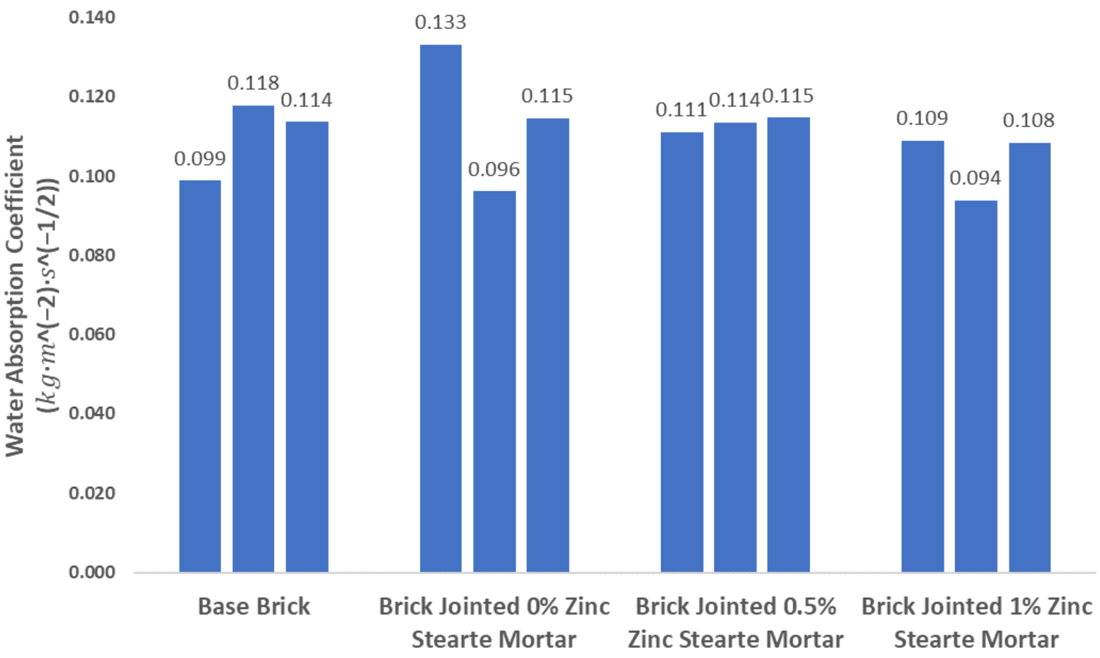


Figure 25. Water Absorption Coefficient of Brick and Brick Jointed with Mortar

For the base mortar and mortar with different concentrations of zinc stearate, the water absorbed versus time is shown in Figure 26. Base mortar shows a similar trend with base brick and brick jointed with mortar: a large ramping in the first two hours of the test. The curve smooths down to flat line after 4 hours of the test, indicating the equilibrium state of water absorption. However, 0.5% w/w zinc stearate mortar and 1% w/w zinc stearate mortar show a flat straight line of water absorbed during the test, indicating after adding zinc stearate to the mortar, the mortar absorb a very limited amount of water. The trend shows the water absorption coefficient can be determined by using the first four data points from the test, because it shows the best straight line covering the points.

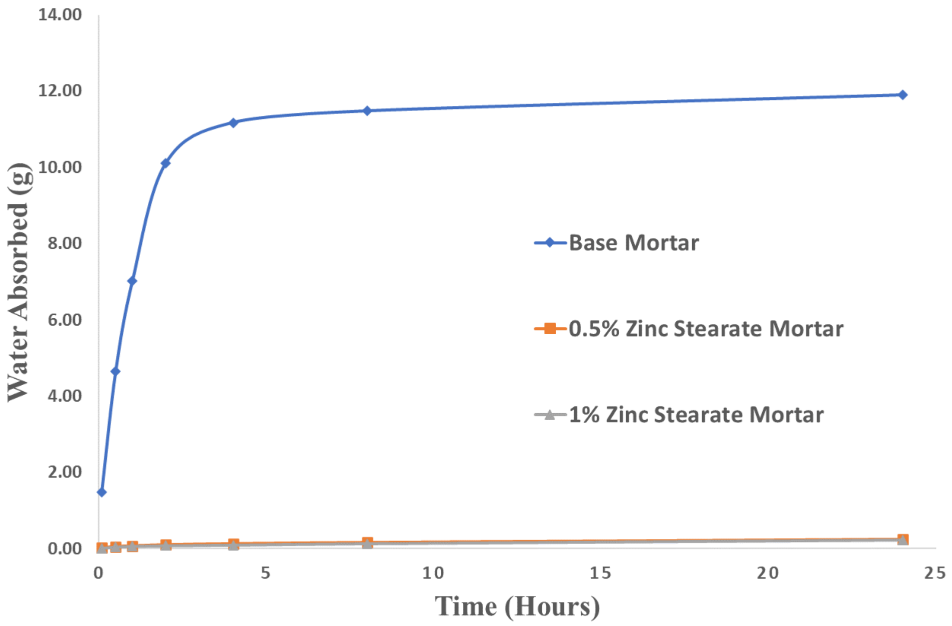


Figure 26. Water Absorption Coefficient of Mortar

Table 3 and Figure 27 shows the calculated results of the water absorption coefficient. Both mortar with 0.5% zinc stearate and 1% zinc stearate have a decreased water absorption coefficient compared to base mortar.

Base mortar has a water absorption coefficient of 0.128 $kg \cdot m^{-2} \cdot s^{-1/2}$. However, when zinc stearate is added to the mortar, both the water absorption coefficient decreases significantly to 0.001 $kg \cdot m^{-2} \cdot s^{-1/2}$ and 0.001 $kg \cdot m^{-2} \cdot s^{-1/2}$. These numbers are very close to 0 which means modified zinc stearate mortar can be considered not absorbing water material.

Table 3 – The Water Absorption Coefficient of Mortar

Specimen	**Water Absorption Coefficient** $(\boldsymbol{kg \cdot m^{-2} \cdot s^{-1/2}})$
0% Zinc Stearate Mortar	0.128 ± 0.0053
0.5% Zinc Stearate Mortar	0.001 ± 0.0002
1% Zinc Stearate Mortar	0.001 ± 0.0001

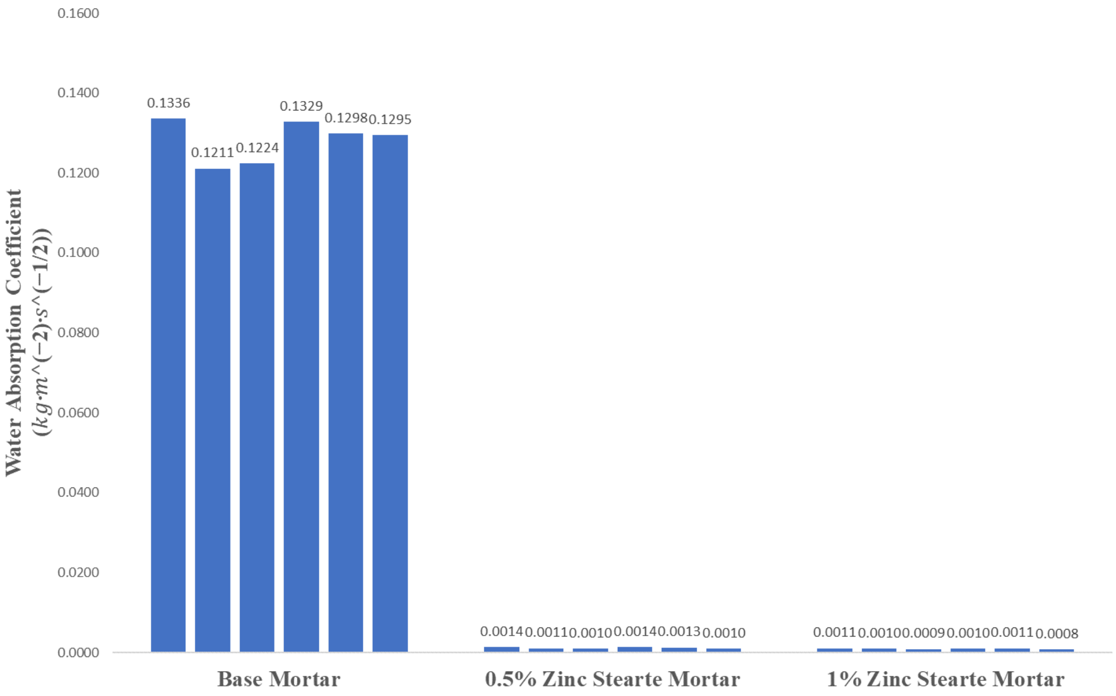


Figure 27. Average Water Absorption Coefficient of different Mortar

3.2 Results of Water Vapor Permeability Test

Table 4 and Figure 28 display the findings of the water vapor permeability test. Table 4 presents the water vapor permeability following adjustment for air layer and surface resistance.

The base brick exhibits remarkably low water vapor permeability, measuring as $0.58 \times 10^{-11} kg \cdot m^{-1} \cdot s^{-1} \cdot Pa^{-1}$ for the dry cup and $0.89 \times 10^{-11} kg \cdot m^{-1} \cdot s^{-1} \cdot Pa^{-1}$ for the wet cup. The modified mortar demonstrates a slight increase in water vapor permeability compared to the base mortar. However, then examining the results of the wet cup test, the water vapor permeability significantly rises in comparison to the base mortar. Notably, the wet cup results between 0.5% zinc stearate and 1% zinc stearate mortar are quite similar.

Table 4 – Water Vapor Permeability of Brick and Brick Jointed with Mortar

Specimen	**Water Vapor Permeability ($kg \cdot m^{-1} \cdot s^{-1} \cdot Pa^{-1} \times 10^{-11}$)** Dry Cup (25% mean RH)	**Wet Cup (75% mean RH)**
Brick	0.58	0.89
0% Zinc Stearate Mortar	1.34	1.95
0.5% Zinc Stearate Mortar	1.48	2.39
1% Zinc Stearate Mortar	1.52	2.44

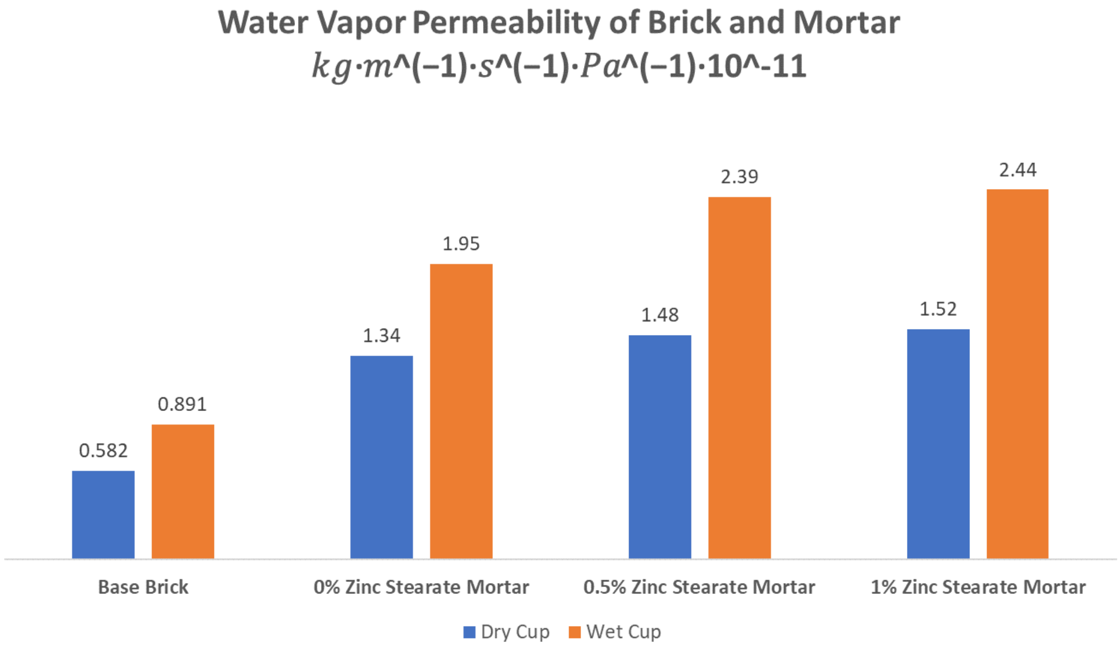


Figure 28. Water Vapor Permeability of Brick and Brick Jointed with Mortar

3.3 Results of Numerical Simulation

The predicted dry and wet cup water vapor diffusion resistance factor, reference water content, free water saturation and water absorption coefficient are shown in Table 5. The calculation of predicted μ value is explained in Appendix C. Reference water content (w80) [22] is water content in specimen at a relative humidity of 0.8 (80%). This value is considered as equivalent to water absorbed in the first 5 minutes of the experiment. Free water saturation (wf) [22] is water content in the specimen at a relative humidity of 1 (100%). This value is considered as equivalent to water absorbed by the specimen at the end of the experiment.

Table 5 – Material Properties for Numerical Modelling

Property	**Unit**	**Brick Jointed with Base Mortar**	**Brick Jointed with 0.5% Zinc Stearate Mortar**	**Brick Jointed with 1% Zinc Stearate Mortar**
Water Vapor Diffusion Resistance Factor μ (RH25%)	-	33.23	33.15	33.13
Water Vapor Diffusion Resistance Factor μ (RH75%)	-	21.71	21.6	21.59
Reference Water Content (RH80%)	kg/m^3	22.02	20.79	19.66
Free Water Saturation (RH100%)	kg/m^3	147.75	143.03	139.44
Water Absorption Coefficient	$kg/(m^2s^{0.5})$	0.1146	0.1131	0.1036

The following table 6-9 show the result from WUFI simulation. Total water content in the wall assembly and water content in brick mortar layer are decreasing when zinc stearate is added to the mortar. Brick jointed with 1% zinc stearate mortar demonstrates the least water content which is consistent with the lowest water absorption rate and water vapor permeability of 1% zinc stearate from the experiment.

Comparing the warm year and cold year, the start of the water content in the wall assembly is the same. However, warm year has slight lower water content in the end. Both years have a similar minimum water content while warm year has a slight larger maximum water content comparted to cold year.

Table 6 – Total Water Content in Wall Assembly in Cold Year

Total Water Content $(\boldsymbol{kg/m^2})$	**Start**	**End**	**Min**	**Max**
Brick Jointed with Base Mortar	3.29	14.39	2.91	14.97
Brick Jointed with 0.5% Zinc Stearate Mortar	3.18	13.96	2.80	14.54
Brick Jointed with 1% Zinc Stearate Mortar	3.07	13.63	2.75	14.23

Table 7 – Water Content in Brick Mortar Layer in Cold Year

Water Content in Brick Mortar Layer $(\boldsymbol{kg/m^2})$	**Start**	**End**	**Min**	**Max**
Brick Jointed with Base Mortar	1.98	12.80	1.81	13.35
Brick Jointed with 0.5% Zinc Stearate Mortar	1.87	12.38	1.71	12.92
Brick Jointed with 1% Zinc Stearate Mortar	1.77	12.05	1.65	12.60

Table 8 – Total Water Content in Wall Assembly in Warm Year

Total Water Content $(\boldsymbol{kg/m^2})$	**Start**	**End**	**Min**	**Max**
Brick Jointed with Base Mortar	3.29	14.19	2.90	15.08
Brick Jointed with 0.5% Zinc Stearate Mortar	3.18	13.77	2.80	14.66
Brick Jointed with 1% Zinc Stearate Mortar	3.07	13.46	2.75	14.35

Table 9 – Water Content in Brick Mortar Layer in Warm Year

Water Content in Brick Mortar Layer $(\boldsymbol{kg/m^2})$	**Start**	**End**	**Min**	**Max**
Brick Jointed with Base Mortar	1.98	12.59	1.80	13.33
Brick Jointed with 0.5% Zinc Stearate Mortar	1.87	12.17	1.70	12.90
Brick Jointed with 1% Zinc Stearate Mortar	1.77	11.85	1.63	12.58

Table 10 and 11 are the water content results in cold year without air cavity. Comparing with results from Table6 and 7 which have air cavity design, it shows the total water content has a significant increase in wall assembly if no air cavity is considered. The water content of the brick mortar layer is similar in both designs. Appendix C includes the simulation graphs of the water content in wall assembly. It demonstrates the plywood layer has a significant water content increase year over year without air cavity.

Table 10 – Total Water Content in Wall Assembly in Cold Year without Air Cavity

Total Water Content **(kg/m^2)**	**Start**	**End**	**Min**	**Max**
Brick Jointed with Base Mortar	3.24	16.15	3.12	17.04
Brick Jointed with 0.5% Zinc Stearate Mortar	3.13	15.75	3.01	16.64
Brick Jointed with 1% Zinc Stearate Mortar	3.03	15.59	2.91	16.46

Table 11 – Total Water Content in Brick Mortar Layer in Cold Year without Air Cavity

Water Content in Brick Mortar Layer **(kg/m^2)**	**Start**	**End**	**Min**	**Max**
Brick Jointed with Base Mortar	1.98	12.74	1.9	13.35
Brick Jointed with 0.5% Zinc Stearate Mortar	1.87	12.31	1.79	12.92
Brick Jointed with 1% Zinc Stearate Mortar	1.77	11.99	1.69	12.6

4. Conclusion and Future Work

1. This study demonstrates that it is possible to reduce the water content of the brick wall assembly through appropriate mortar mix design.
2. In this study, the addition of zinc stearate to the mortar has been found to decrease the water absorption coefficient while simultaneously enhancing water vapor permeability.
3. The utilization of zinc stearate as an admixture in mortar mix exhibits potential for the development of high- performance brick joints with improved characteristics. Compared to commonly used brick mortar materials in North America. These joints exhibit a relatively lower capacity for liquid water absorption and a higher capacity for water vapor transmission.
4. To optimize the mix design of high-performance materials that maximize moisture management capability, additional experimental and numerical modelling investigations are needed to understand the comprehensive hygrothermal behavior of brick mortar joints and the wall system.
5. Before concluding the long-term performance of the mortar mix developed in this study, it is necessary to conduct investigations on the durability and strength of the brick mortar joints.

6. Numerical modelling results demonstrate that employing high-performance brick mortar materials can substantially enhance the moisture management capability of brick walls in the marine-warm and humid climate of Vancouver, BC, Canada.
7. Numerical modelling results indicate that air cavity design in brick wall assembly is essential for moisture management. It has a significant role in reducing water content.

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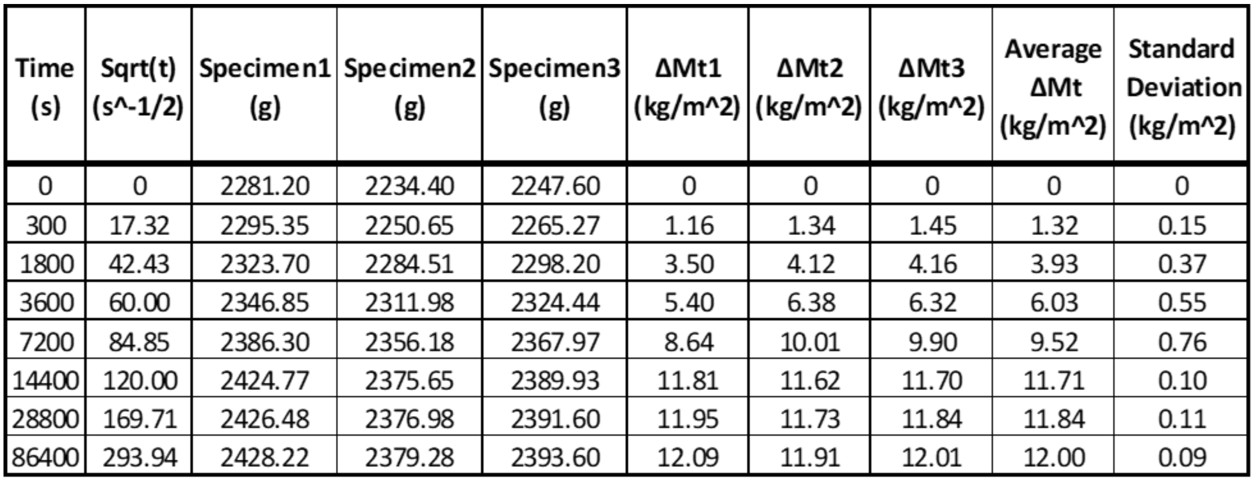
Appendix

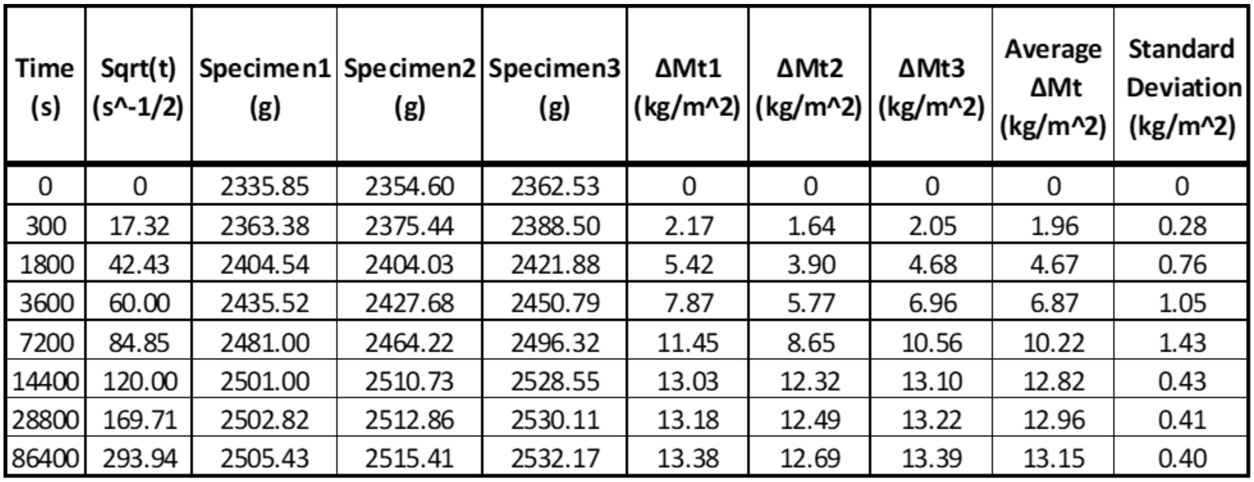
A: Liquid Water Absorption Coefficient

A1: Water Absorption Test Data of Base Brick



Time (s)	Sqrt(t) (s^-1/2)	Specimen1 (g)	Specimen2 (g)	Specimen3 (g)	ΔMt1 (kg/m^2)	ΔMt2 (kg/m^2)	ΔMt3 (kg/m^2)	Average ΔMt (kg/m^2)	Standard Deviation (kg/m^2)
0	0	2281.20	2234.40	2247.60	0	0	0	0	0
300	17.32	2295.35	2250.65	2265.27	1.16	1.34	1.45	1.32	0.15
1800	42.43	2323.70	2284.51	2298.20	3.50	4.12	4.16	3.93	0.37
3600	60.00	2346.85	2311.98	2324.44	5.40	6.38	6.32	6.03	0.55
7200	84.85	2386.30	2356.18	2367.97	8.64	10.01	9.90	9.52	0.76
14400	120.00	2424.77	2375.65	2389.93	11.81	11.62	11.70	11.71	0.10
28800	169.71	2426.48	2376.98	2391.60	11.95	11.73	11.84	11.84	0.11
86400	293.94	2428.22	2379.28	2393.60	12.09	11.91	12.01	12.00	0.09

A2: Water Absorption Test Data of Base Jointed with Base Mortar



Time (s)	Sqrt(t) (s^-1/2)	Specimen1 (g)	Specimen2 (g)	Specimen3 (g)	ΔMt1 (kg/m^2)	ΔMt2 (kg/m^2)	ΔMt3 (kg/m^2)	Average ΔMt (kg/m^2)	Standard Deviation (kg/m^2)
0	0	2335.85	2354.60	2362.53	0	0	0	0	0
300	17.32	2363.38	2375.44	2388.50	2.17	1.64	2.05	1.96	0.28
1800	42.43	2404.54	2404.03	2421.88	5.42	3.90	4.68	4.67	0.76
3600	60.00	2435.52	2427.68	2450.79	7.87	5.77	6.96	6.87	1.05
7200	84.85	2481.00	2464.22	2496.32	11.45	8.65	10.56	10.22	1.43
14400	120.00	2501.00	2510.73	2528.55	13.03	12.32	13.10	12.82	0.43
28800	169.71	2502.82	2512.86	2530.11	13.18	12.49	13.22	12.96	0.41
86400	293.94	2505.43	2515.41	2532.17	13.38	12.69	13.39	13.15	0.40

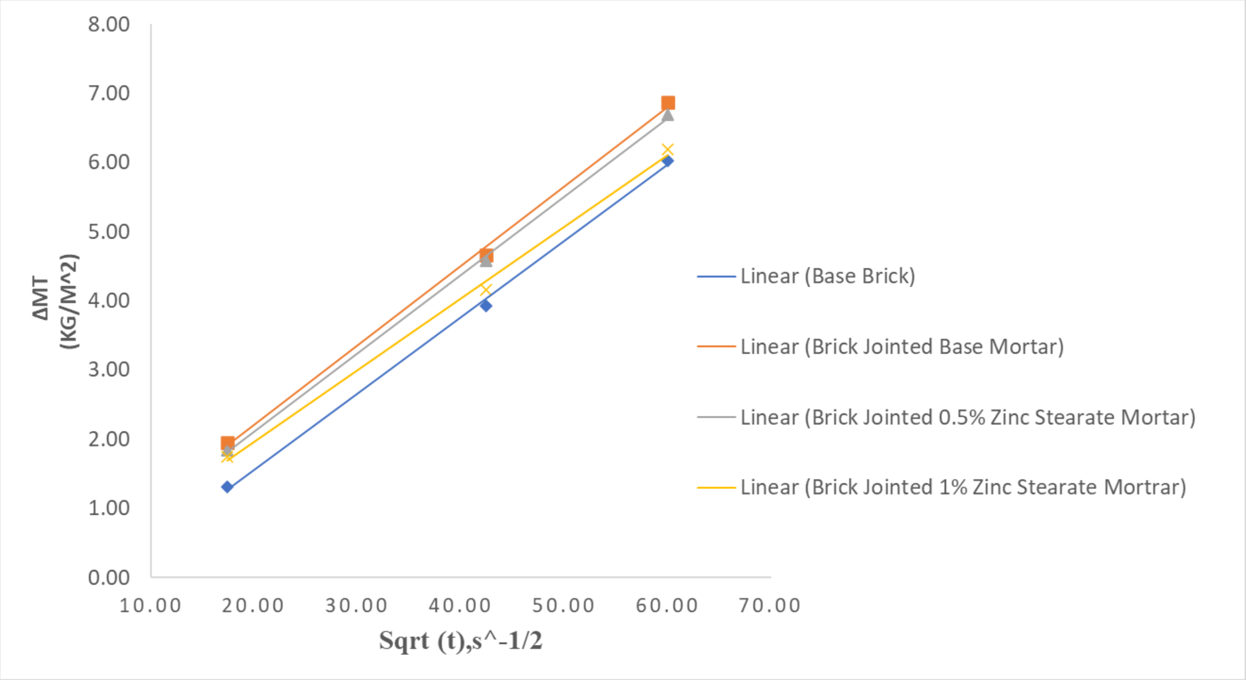
A3: Water Absorption Test Data of Base Jointed with 0.5% Zinc Stearate Mortar

Time (s)	sqrt(t) (s^-1/2)	Specimen1 (g)	Specimen2 (g)	Specimen3 (g)	ΔMt1 (kg/m^2)	ΔMt2 (kg/m^2)	ΔMt3 (kg/m^2)	Average ΔMt (kg/m^2)	Standard Deviation (kg/m^2)
0	0	2380.41	2376.54	2370.33	0	0	0	0	0
300	17.32	2404.00	2401.46	2394.56	1.80	1.90	1.85	1.85	0.05
1800	42.43	2438.05	2437.89	2431.56	4.39	4.67	4.66	4.58	0.16
3600	60.00	2466.60	2465.17	2458.96	6.56	6.75	6.75	6.69	0.11
7200	84.85	2511.87	2518.01	2508.61	10.01	10.77	10.53	10.44	0.39
14400	120.00	2542.51	2538.70	2531.54	12.35	12.35	12.28	12.32	0.04
28800	169.71	2543.97	2540.07	2533.25	12.46	12.45	12.41	12.44	0.03
86400	293.94	2547.99	2543.99	2536.56	12.76	12.75	12.66	12.73	0.06

A4: Water Absorption Test Data of Base Jointed with 1% Zinc Stearate Mortar

Time (s)	Sqrt(t) (s^-1/2)	Specimen1 (g)	Specimen2 (g)	Specimen3 (g)	ΔMt1 (kg/m^2)	ΔMt2 (kg/m^2)	ΔMt3 (kg/m^2)	Average ΔMt (kg/m^2)	Standard Deviation (kg/m^2)
0	0	2325.78	2363.29	2405.68	0	0	0	0	0
300	17.32	2348.15	2384.03	2430.81	1.73	1.60	1.91	1.75	0.15
1800	42.43	2380.82	2412.36	2463.93	4.26	3.80	4.42	4.16	0.32
3600	60.00	2408.52	2436.06	2492.07	6.40	5.63	6.55	6.19	0.50
7200	84.85	2451.24	2473.69	2535.99	9.70	8.54	9.88	9.38	0.73
14400	120.00	2484.15	2516.98	2565.15	12.25	11.89	12.10	12.08	0.18
28800	169.71	2485.59	2519.05	2566.79	12.36	12.05	12.22	12.21	0.16
86400	293.94	2488.13	2521.74	2569.24	12.56	12.26	12.41	12.41	0.15

A5: Linear Line of Brick and Jointed with Mortar with First 3 Data Points



A6: Line of Equation of Brick and Jointed with Mortar with First 3 Data Points

The slope of the equation of the water absorption coefficient.

Base Brick: $y = 0.1100x - 0.6329$ $R^2 = 0.9984$

Brick Jointed with Base Mortar: $y = 0.1146x - 0.0767$ $R^2 = 0.9983$

Brick Jointed with 0.5% Zinc Stearate Mortar: $y = 0.1131x - 0.1450$ $R^2 = 0.9992$

Brick Jointed with 1% Zinc Stearate Mortar: $y = 0.1036x - 0.1040$ $R^2 = 0.9972$

A7. Water Absorption Coefficient of Each Test Specimen of Base Brick

Base Brick	**Water Absorption Coefficient ($kg \cdot m^{-2} \cdot s^{-1/2}$)**
Specimen1	0.0988
Specimen2	0.1177
Specimen3	0.1136
Average	0.1100
Standard Deviation	0.0099

A8. Water Absorption Coefficient of Each Test Specimen of Brick Jointed with Base Mortar

Brick Jointed Base Mortar	**Water Absorption Coefficient ($kg \cdot m^{-2} \cdot s^{-1/2}$)**
Specimen1	0.1331
Specimen2	0.0961
Specimen3	0.1145
Average	0.1146
Standard Deviation	0.0185

A9. Water Absorption Coefficient of Each Test Specimen of Brick Jointed with 0.5% Zinc Stearate Mortar

Brick Jointed 0.5% Zinc Stearate Mortar	**Water Absorption Coefficient ($kg \cdot m^{-2} \cdot s^{-1/2}$)**
Specimen1	0.1111
Specimen2	0.1135
Specimen3	0.1147
Average	0.1131
Standard Deviation	0.0018

A10. Water Absorption Coefficient of Each Test Specimen of Brick Jointed with 1% Zinc Stearate Mortar

Brick Jointed 1% Zinc Stearate Mortar	**Water Absorption Coefficient $(kg \cdot m^{-2} \cdot s^{-1/2})$**
Specimen1	0.1088
Specimen2	0.0938
Specimen3	0.1083
Average	0.1036
Standard Deviation	0.0085

A11: Water Absorption Test Data of Base Mortar

Time (s)	**sqrt(t) (s^-1/2)**	**Specimen1 (g)**	**Specimen2 (g)**	**Specimen3 (g)**	**Specimen4 (g)**	**Specimen5 (g)**	**Specimen6 (g)**	**Average ΔMt (kg/m^2)**	**Standard Deviation (kg/m^2)**
0	0	204.76	204.16	197.4	208.68	207.1	215.52	0	0
300	17.32	207.38	207.23	200.23	211.21	209.84	218.15	1.49	0.11
1800	42.43	213.67	212.87	206.03	216.98	215.46	223.98	4.65	0.13
3600	60.00	218.09	216.87	210.08	221.54	220.03	228.51	7.02	0.13
7200	84.85	223.96	222.26	215.41	227.65	225.87	234.15	10.12	0.26
14400	120.00	225.92	224.93	217.59	228.98	227.87	235.67	11.17	0.22
28800	169.71	226.23	225.27	217.91	229.69	228.16	237.07	11.48	0.20
86400	293.94	226.96	225.92	218.42	230.76	228.85	238.02	11.89	0.28

A12: Water Absorption Test Data of 0.5% Zinc Stearate Mortar

Time (s)	**sqrt(t) (s^-1/2)**	**Specimen1 (g)**	**Specimen2 (g)**	**Specimen3 (g)**	**Specimen4 (g)**	**Specimen5 (g)**	**Specimen6 (g)**	**Average ΔMt (kg/m^2)**	**Standard Deviation (kg/m^2)**
0	0	197.21	194.96	195.41	204.21	208.61	203.99	0	0
300	17.32	197.29	194.98	195.43	204.24	208.64	204.04	0.02	0.01
1800	42.43	197.33	195.04	195.50	204.34	208.69	204.12	0.05	0.01
3600	60.00	197.40	195.09	195.52	204.37	208.72	204.14	0.07	0.02
7200	84.85	197.47	195.12	195.56	204.42	208.82	204.18	0.10	0.02
14400	120.00	197.53	195.20	195.65	204.45	208.88	204.21	0.13	0.02
28800	169.71	197.60	195.28	195.72	204.50	208.94	204.28	0.17	0.02
86400	293.94	197.80	195.51	195.91	204.70	208.96	204.48	0.26	0.04

A13: Water Absorption Test Data of 1% Zinc Stearate Mortar

Time (s)	sqrt(t) (s^-1/2)	Specimen1 (g)	Specimen2 (g)	Specimen3 (g)	Specimen4 (g)	Specimen5 (g)	Specimen6 (g)	Average ΔMt (kg/m^2)	Standard Deviation (kg/m^2)
0	0	188.13	186.07	179.19	182.09	173.69	177.01	0	0
300	17.32	188.16	186.11	179.25	182.10	173.71	177.03	0.02	0.01
1800	42.43	188.20	186.15	179.28	182.18	173.80	177.10	0.05	0.01
3600	60.00	188.25	186.18	179.33	182.23	173.82	177.13	0.07	0.01
7200	84.85	188.30	186.24	179.36	182.23	173.86	177.14	0.08	0.01
14400	120.00	188.36	186.29	179.38	182.25	173.88	177.16	0.10	0.02
28800	169.71	188.42	186.41	179.50	182.28	173.93	177.20	0.13	0.03
86400	293.94	188.60	186.62	179.70	182.43	174.10	177.38	0.23	0.04

A14: Line of Equation of Brick and Jointed with Mortar with First 4 Data Points

The slope of the equation of the water absorption coefficient.

Base Mortar: $y = 0.1282x - 0.7388$ $R^2 = 0.9998$

0.5% Zinc Stearate Mortar: $y = 0.0012x + 0.0007$ $R^2 = 0.9970$

1% Zinc Stearate Mortar: $y = 0.0010x + 0.0014$ $R^2 = 0.9800$

A15. Brick Mortar Joint Liquid Water Content Absorbed for Brick jointed with Base Mortar

Time (s)	Base Brick Portion Water Absorbed (g)	Base Mortar Portion Water Absorbed (g)	Total Water Absorbed (g)	Experimental Brick Jointed with Base Mortar Water Absorbed (g)	Brick Mortar Joint Water Absorbed (g)
300	21.80	0.24	22.04	24.78	2.74
1800	53.40	0.59	53.99	59.16	5.16
3600	75.52	0.84	76.36	87.00	10.65

A16. Brick Mortar Joint Liquid Water Content Absorbed for Brick jointed with 0.5% Zinc Stearate Mortar

Time (s)	Base Brick Portion Water Absorbed (g)	0.5% Zinc Stearate Mortar Portion Water Absorbed (g)	Total Water Absorbed (g)	Experimental Brick Jointed with 0.5% Zinc Stearate Mortar Water Absorbed (g)	Brick Mortar Joint Water Absorbed (g)
300	21.80	0.00	21.80	24.25	2.44
1800	53.40	0.01	53.41	60.07	6.67
3600	75.52	0.01	75.53	87.82	12.29

A17. Brick Mortar Joint Liquid Water Content Absorbed for Brick jointed with 1% Zinc Stearate Mortar

Time (s)	Base Brick Portion Water Absorbed (g)	1% Zinc Stearate Mortar Portion Water Absorbed (g)	Total Water Absorbed (g)	Experimental Brick Jointed with 1% Zinc Stearate Mortar Water Absorbed (g)	Brick Mortar Joint Water Absorbed (g)
300	21.80	0.00	21.80	22.75	0.94
1800	53.40	0.00	53.41	54.12	0.71
3600	75.52	0.01	75.53	80.63	5.11

A18. Water Absorption Coefficient of Each Test Specimen of Base Mortar

Base Mortar	Water Absorption Coefficient ($kg \cdot m^{-2} \cdot s^{-1/2}$)
Specimen1	0.1336
Specimen2	0.1211
Specimen3	0.1224
Specimen4	0.1329
Specimen5	0.1298
Specimen6	0.1295
Average	0.1282
Standard Deviation	0.0053

A19. Water Absorption Coefficient of Each Test Specimen of 0.5% Zinc Stearate Mortar

0.5% Zinc Stearate Mortar	**Water Absorption Coefficient ($\boldsymbol{kg \cdot m^{-2} \cdot s^{-1/2}}$)**
Specimen1	0.0014
Specimen2	0.0011
Specimen3	0.0010
Specimen4	0.0014
Specimen5	0.0013
Specimen6	0.001
Average	0.0012
Standard Deviation	0.0002

A20. Water Absorption Coefficient of Each Test Specimen of 1% Zinc Stearate Mortar

1% Zinc Stearate Mortar	**Water Absorption Coefficient ($\boldsymbol{kg \cdot m^{-2} \cdot s^{-1/2}}$)**
Specimen1	0.0011
Specimen2	0.0010
Specimen3	0.0009
Specimen4	0.0010
Specimen5	0.0011
Specimen6	0.0008
Average	0.0010
Standard Deviation	0.0001

A20. Bulk Density of Base Brick and Brick Mortar Joints before Coating

Specimen	**Average Bulk Density ($\boldsymbol{kg/m^3}$)**
Base Brick	2078 ± 23.90
Brick Jointed with Base Mortar	2190 ± 19.00
Brick Jointed with 0.5% Zinc Stearate Mortar	2213 ± 5.51
Brick Jointed with 1% Zinc Stearate Mortar	2193 ± 38.50

A20. Bulk Density of Mortar before Coating

Specimen	Average Bulk Density (kg/m^3)
Base Mortar	2200 ± 41.63
0.5% Zinc Stearate Mortar	2070 ± 20.00
1% Zinc Stearate Mortar	1850 ± 45.83

B: Water Vapor Permeability

B1: Water Vapor Permeability Dry Cup Test Data of Base Brick

Elapsed Time (h)	Specimen1 (g)	Specimen2 (g)	Specimen3 (g)	Blank Specimen (g)	Chamber Temperature (℃)	Chamber RH (%)	Barometric Pressure (kPa)
0	2371.29	2346.16	2323.48	949.23	NA	NA	NA
48	2372.26	2347.09	2324.22	949.10	32.1	50.8	101.45
71	2372.65	2347.54	2324.65	949.02	32.1	50.4	101.52
96	2373.24	2348.08	2325.31	949.08	32.1	49.8	101.64
120	2373.71	2348.62	2325.75	949.12	32.1	50.6	101.61
144	2374.22	2349.15	2326.25	949.08	32.1	50.7	101.88
168	2374.71	2349.65	2326.82	949.08	32.2	49.8	101.85

B2: Water Vapor Permeability Wet Cup Test Data of Base Brick

Elapsed Time (h)	Specimen1 (g)	Specimen2 (g)	Specimen3 (g)	Blank Specimen (g)	Chamber Temperature (℃)	Chamber RH (%)	Barometric Pressure (kPa)
0	2338.23	2381.59	2320.53	949.20	NA	NA	NA
24	2337.57	2380.94	2319.83	949.09	32.1	50.7	101.42
48	2336.88	2380.25	2319.11	949.09	32.1	50.5	101.96
72	2336.11	2379.51	2318.38	949.09	32.1	50.4	101.91
96	2335.28	2378.84	2317.68	949.07	32.1	50.7	102.08
120	2334.45	2378.12	2316.99	949.07	31.8	51.0	102.09
144	2333.44	2377.55	2316.41	949.10	32.3	49.6	102.02

B3: Water Vapor Permeability Dry Cup Test Data of Base Mortar

Elapsed Time (h)	Specimen1 (g)	Specimen2 (g)	Specimen3 (g)	Blank Specimen (g)	Chamber Temperature (℃)	Chamber RH (%)	Barometric Pressure (kPa)
0	2421.39	2351.27	2251.56	1795.88	NA	NA	NA
29	2423.89	2353.50	2254.82	1795.60	32.5	50.3	100.63
50	2426.06	2355.61	2257.31	1795.47	32.1	50.8	101.45
78	2429.14	2358.68	2260.87	1795.46	32.1	50.4	101.52
100	2431.48	2361.06	2263.52	1795.42	32.4	49.4	101.38
120	2433.60	2363.18	2265.99	1795.40	32.2	50.1	101.79
142	2435.99	2365.58	2268.67	1795.43	32.1	49.6	101.40

B4: Water Vapor Permeability Wet Cup Test Data of Base Mortar

Elapsed Time (h)	Specimen1 (g)	Specimen2 (g)	Specimen3 (g)	Blank Specimen (g)	Chamber Temperature (℃)	Chamber RH (%)	Barometric Pressure (kPa)
0	2181.35	2170.82	2071.11	1806.81	NA	NA	NA
25	2177.94	2166.64	2067.22	1805.76	32.6	50.5	101.25
49	2173.87	2162.37	2062.83	1805.21	32.6	50.1	101.12
73	2169.91	2158.27	2058.59	1804.90	32.7	50.0	101.24
90	2167.15	2155.41	2055.49	1804.73	32.6	50.0	101.11
97	2165.99	2154.17	2054.25	1804.65	32.6	49.7	101.02
114	2163.21	2151.29	2051.25	1804.56	32.7	49.7	100.60

B5: Water Vapor Permeability Dry Cup Test Data of 0.5% Zinc Stearate Mortar

Elapsed Time (h)	Specimen1 (g)	Specimen2 (g)	Specimen3 (g)	Blank Specimen (g)	Chamber Temperature (℃)	Chamber RH (%)	Barometric Pressure (kPa)
0	2336.08	2154.50	2407.73	1649.57	NA	NA	NA
24	2339.34	2157.89	2410.57	1649.63	32.5	48.7	102.08
48	2342.60	2161.12	2413.55	1649.69	32.5	49.3	101.12
69	2345.45	2163.94	2416.13	1649.68	32.5	49.2	101.05
96	2348.36	2166.88	2420.21	1649.78	32.6	48.9	101.22
107	2350.49	2168.96	2420.65	1649.73	32.8	48.7	101.38
120	2352.19	2170.75	2422.25	1649.79	32.5	50.9	101.68

B6: Water Vapor Permeability Wet Cup Test Data of 0.5% Zinc Stearate Mortar

Elapsed Time (h)	Specimen1 (g)	Specimen2 (g)	Specimen3 (g)	Blank Specimen (g)	Chamber Temperature (℃)	Chamber RH (%)	Barometric Pressure (kPa)
0	2202.21	2065.75	2258.33	1649.76	NA	NA	NA
33	2197.86	2061.56	2254.18	1649.74	32.7	50.6	101.89
54	2193.93	2057.43	2250.97	1649.84	32.6	50.2	101.25
77	2189.86	2053.43	2245.86	1649.83	32.4	50.0	101.25
91	2187.12	2050.87	2243.35	1649.82	32.5	50.2	101.38
100	2185.48	2049.03	2241.69	1649.86	32.6	50.2	101.48
111	2183.65	2046.85	2239.21	1649.85	32.4	50.2	101.28

B7: Water Vapor Permeability Dry Cup Test Data of 1% Zinc Stearate Mortar

Elapsed Time (h)	Specimen1 (g)	Specimen2 (g)	Specimen3 (g)	Blank Specimen (g)	Chamber Temperature (℃)	Chamber RH (%)	Barometric Pressure (kPa)
0	2180.02	2264.91	2292.42	1626.49	NA	NA	NA
28	2183.96	2268.48	2296.24	1626.57	32.3	50.0	101.58
50	2186.96	2273.31	2296.26	1626.63	32.4	49.4	101.38
70	2189.74	2273.85	2302.00	1626.68	32.2	50.1	101.28
92	2192.78	2276.64	2305.03	1626.74	32.1	49.6	101.48
118	2196.12	2279.78	2308.36	1626.84	32.1	50.7	101.42
142	2199.33	2282.79	2311.54	1626.85	32.1	50.5	101.96

B8: Water Vapor Permeability Wet Cup Test Data of 1% Zinc Stearate Mortar

Elapsed Time (h)	Specimen1 (g)	Specimen2 (g)	Specimen3 (g)	Blank Specimen (g)	Chamber Temperature (℃)	Chamber RH (%)	Barometric Pressure (kPa)
0	1946.48	1942.20	2029.33	1612.81	NA	NA	NA
22	1942.68	1938.96	2026.04	1613.02	32.6	50.5	101.24
46	1938.15	1934.88	2021.39	1613.14	32.6	50.1	101.12
70	1933.28	1930.54	2016.90	1613.27	32.7	50.0	101.24
87	1929.96	1927.66	2013.64	1613.44	32.6	50.0	101.11
94	1928.55	1926.43	2012.25	1613.48	32.6	49.7	101.02
111	1925.18	1923.37	2009.11	1613.58	32.7	49.7	100.60

B9: Water Vapor Permeability Results of Base Brick (Before Correction)

Base Brick	**Water Vapor Permeability $(kg \cdot m^{-1} \cdot s^{-1} \cdot Pa^{-1})$ Dry Cup**	**Water Vapor Permeability $(kg \cdot m^{-1} \cdot s^{-1} \cdot Pa^{-1})$ Wet Cup**
Specimen1	5.61E-12	9.56E-12
Specimen2	5.86E-12	7.97E-12
Specimen3	5.89E-12	8.02E-12
Average	5.82E-12	8.52E-12
Standard Deviation	1.51E-13	9.04E-13

B10: Water Vapor Permeability Results of Base Mortar (Before Correction)

Base Mortar	**Water Vapor Permeability $(kg \cdot m^{-1} \cdot s^{-1} \cdot Pa^{-1})$ Dry Cup**	**Water Vapor Permeability $(kg \cdot m^{-1} \cdot s^{-1} \cdot Pa^{-1})$ Wet Cup**
Specimen1	1.25E-11	1.69E-11
Specimen2	1.25E-11	1.77E-11
Specimen3	1.43E-11	1.85E-11
Average	1.31E-11	1.77E-11
Standard Deviation	1.04E-12	8.00E-13

B11: Water Vapor Permeability Results of 0.5% Zinc Stearate Mortar (Before Correction)

0.5% Zinc Stearate Mortar	**Water Vapor Permeability $(kg \cdot m^{-1} \cdot s^{-1} \cdot Pa^{-1})$ Dry Cup**	**Water Vapor Permeability $(kg \cdot m^{-1} \cdot s^{-1} \cdot Pa^{-1})$ Wet Cup**
Specimen1	1.46E-11	2.07E-11
Specimen2	1.45E-11	2.11E-11
Specimen3	1.36E-11	2.19E-11
Average	1.44E-11	2.12E-11
Standard Deviation	5.51E-13	6.11E-13

B12: Water Vapor Permeability Results of 1% Zinc Stearate Mortar (Before Correction)

1% Zinc Stearate Mortar	Water Vapor Permeability $(kg \cdot m^{-1} \cdot s^{-1} \cdot Pa^{-1})$ Dry Cup	Water Vapor Permeability $(kg \cdot m^{-1} \cdot s^{-1} \cdot Pa^{-1})$ Wet Cup
Specimen1	1.51E-11	2.27E-11
Specimen2	1.31E-11	2.02E-11
Specimen3	1.62E-11	2.19E-11
Average	1.48E-11	2.16E-11
Standard Deviation	1.57E-12	1.28E-12

C: Numerical Simulation

C1: Calculation of Water Vapor Diffusion Resistance μ (dry cup)

	Unit	Brick	0% Mortar	0.5% Mortar	1% Mortar
Permanence	$\frac{kg}{m^2 sPa}$	2.29E-10	7.42E-10	8.21E-10	8.43E-10
Permanence	$\frac{ng}{m^2 sPa}$	2.29E+02	7.42E+02	8.21E+02	8.43E+02
Multiply by 0.001	$\frac{g}{MNS}$	2.29E-01	7.42E-01	8.21E-01	8.43E-01
Reciprocate	$\frac{MNS}{g}$	4.37E+00	1.35E+00	1.22E+00	1.19E+00
Equivalent Air layer Thickness Sd	m	8.73E-01	2.70E-01	2.44E-01	2.37E-01
Water Vapor Diffusion Resistance μ		34.38	14.97	13.53	13.18

MNS/g – Mega-Newton seconds per gram

Equation and method of converting water vapor permeability to water vapor diffusion resistance factor [23]

C2: Calculation of Water Vapor Diffusion Resistance μ (wet cup)

	Unit	Brick	0% Mortar	0.5% Mortar	1% Mortar
Permanence	$\frac{kg}{m^2sPa}$	3.51E-10	1.08E-09	1.33E-09	1.36E-09
Permanence	$\frac{ng}{m^2sPa}$	3.51E+02	1.08E+03	1.33E+03	1.36E+03
Multiply by 0.001	$\frac{g}{MNS}$	3.51E-01	1.08E+00	1.33E+00	1.36E+00
Reciprocate	$\frac{MNS}{g}$	2.85E+00	9.26E-01	7.52E-01	7.35E-01
Equivalent Air layer Thickness Sd	m	5.70E-01	1.85E-01	1.50E-01	1.47E-01
Water Vapor Diffusion Resistance μ		22.43	10.29	8.35	8.17

C3: Calculation of Predicting Brick Jointed with Mortar (dry cup)

Brick size - 190x64x89 in mm

Mortar size - 12x64x89 in mm

In a set of brick jointed with mortar, consider 94.1% is brick and 5.9% is mortar.

$94.1\% * 34.38 + 5.9\% * 14.97 = 33.23$ (base)

$94.1\% * 34.38 + 5.9\% * 13.53 = 33.15$ (0.5% zinc stearate)

$94.1\% * 34.38 + 5.9\% * 13.18 = 33.13$ (1% zin stearate)

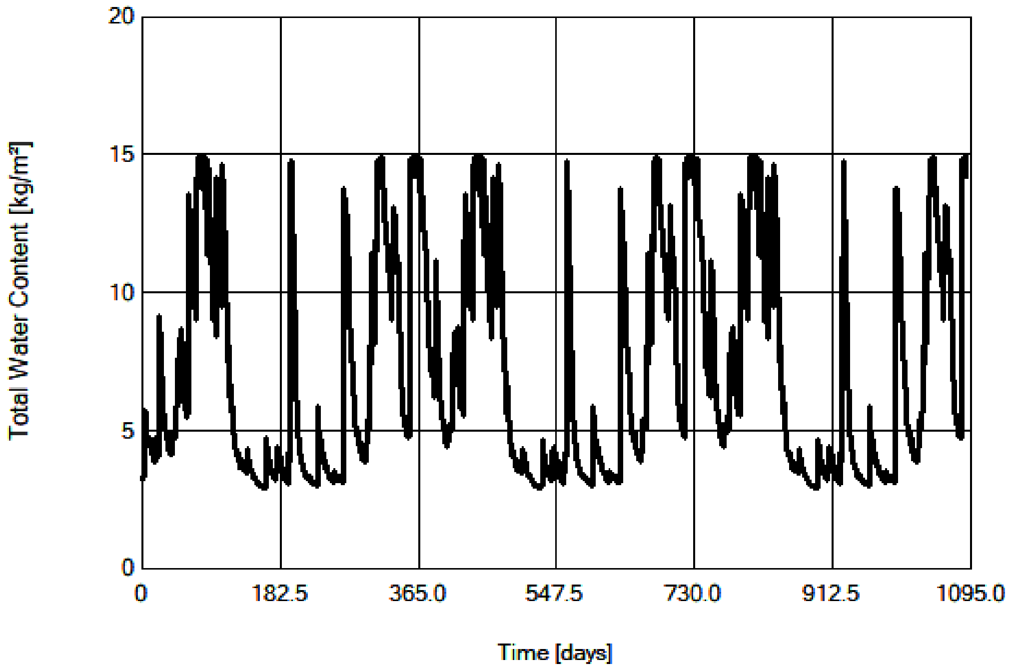
C4: Calculation of Predicting Brick Jointed with Mortar (wet cup)

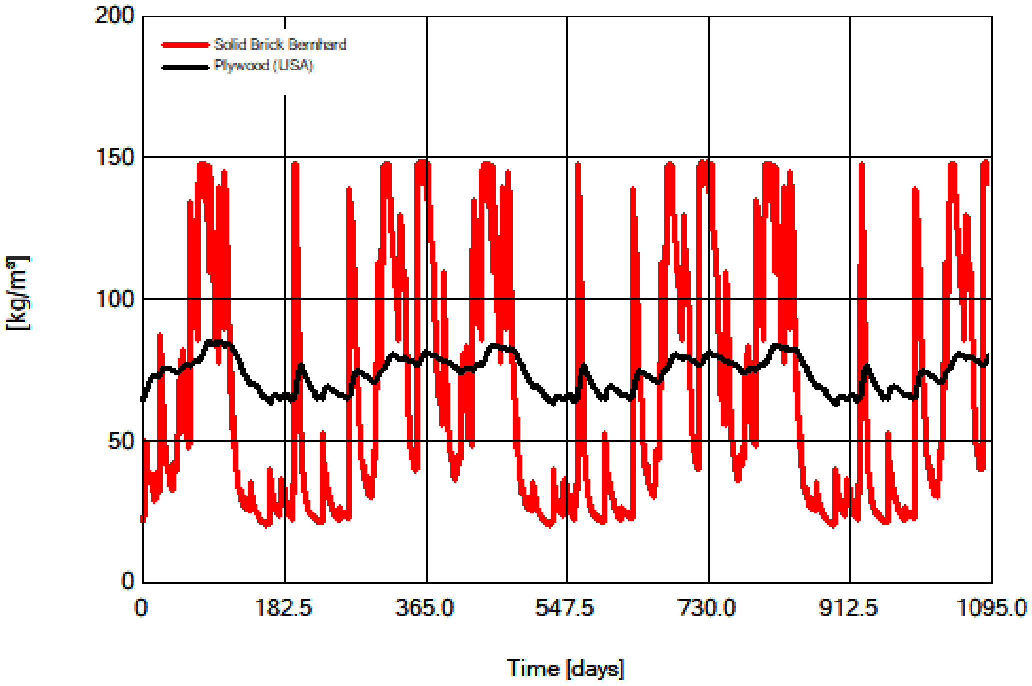
$94.1\% * 22.43 + 5.9\% * 10.29 = 21.71$ (base)

$94.1\% * 22.43 + 5.9\% * 8.35 = 21.60$ (0.5% zinc stearate)

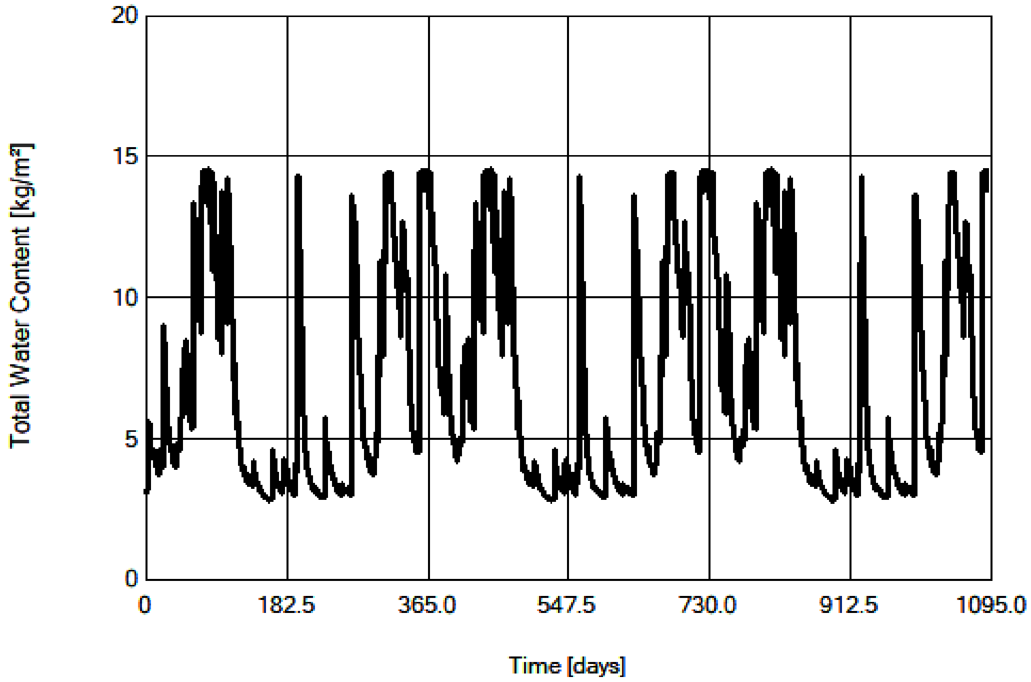
$94.1\% * 22.43 + 5.9\% * 8.17 = 21.59$ (1% zinc stearate)

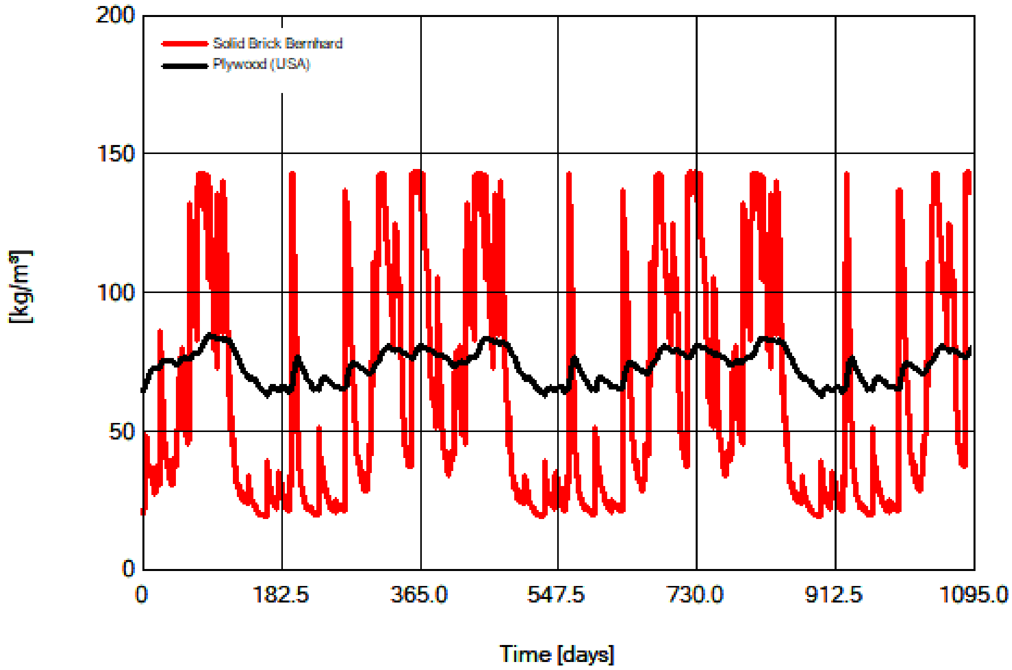
C5: WUFI Graph of Brick Jointed with Base Mortar in Cold Year



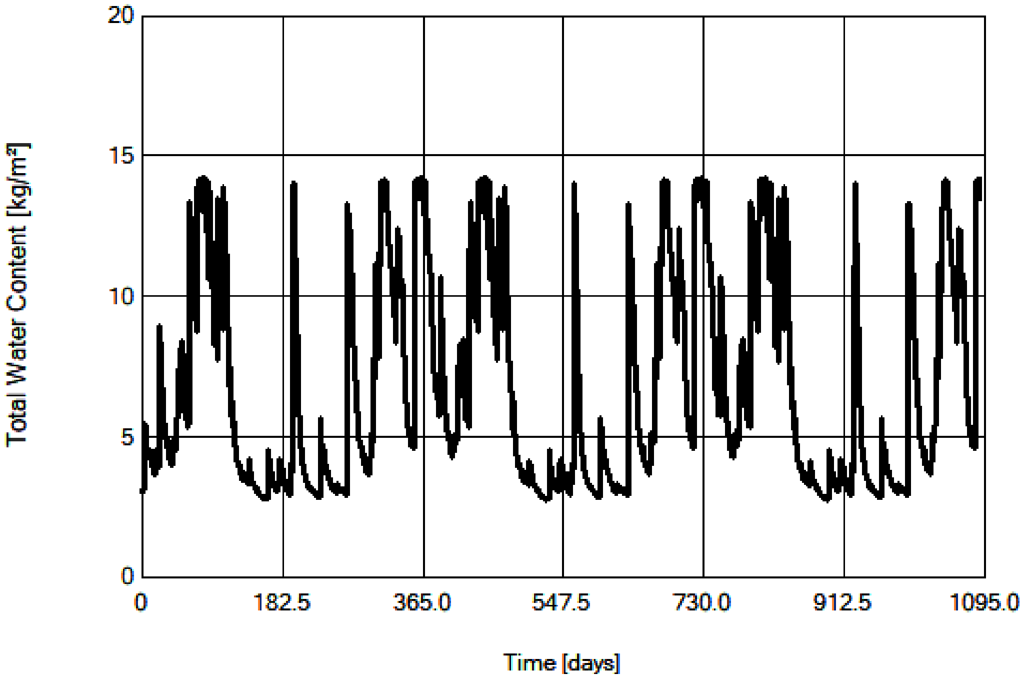


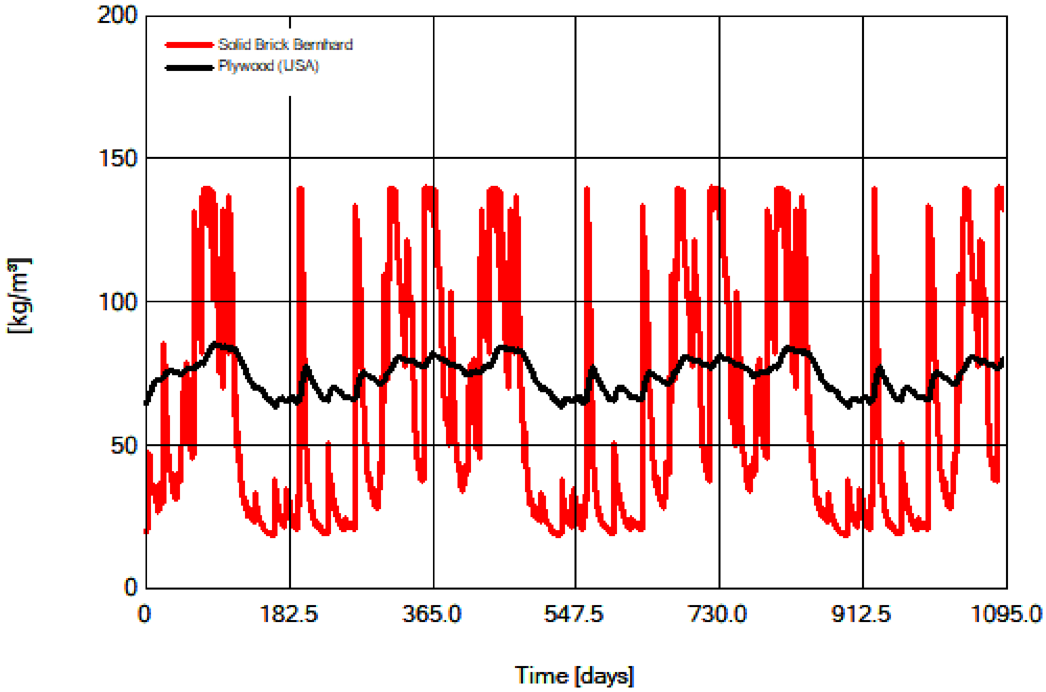
C6: WUFI Graph of Brick Jointed with 0.5% Zinc Stearate Base Mortar in Cold Year



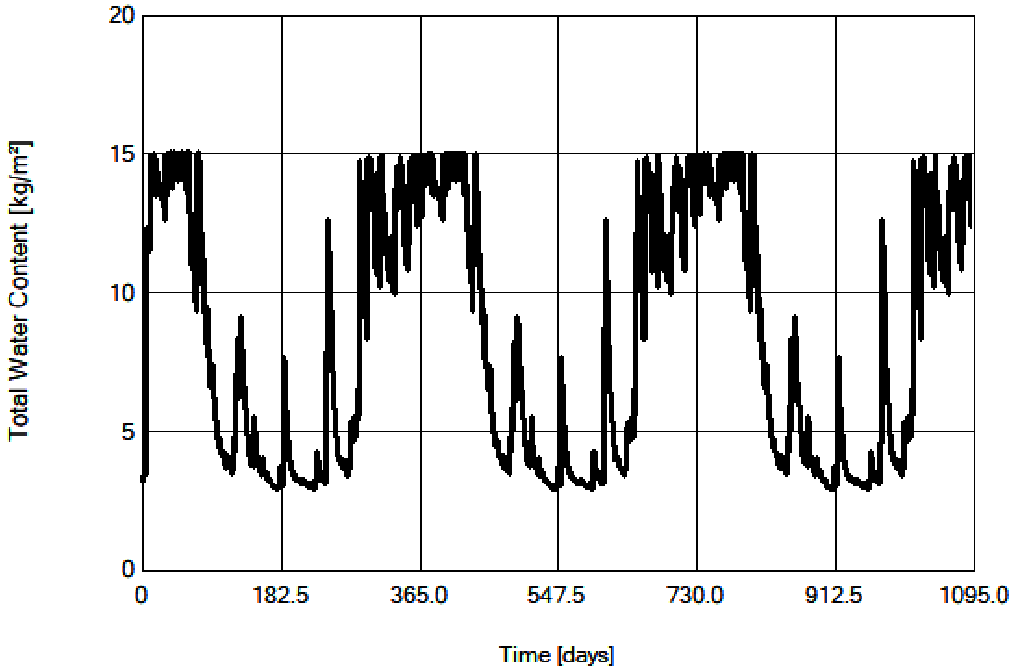


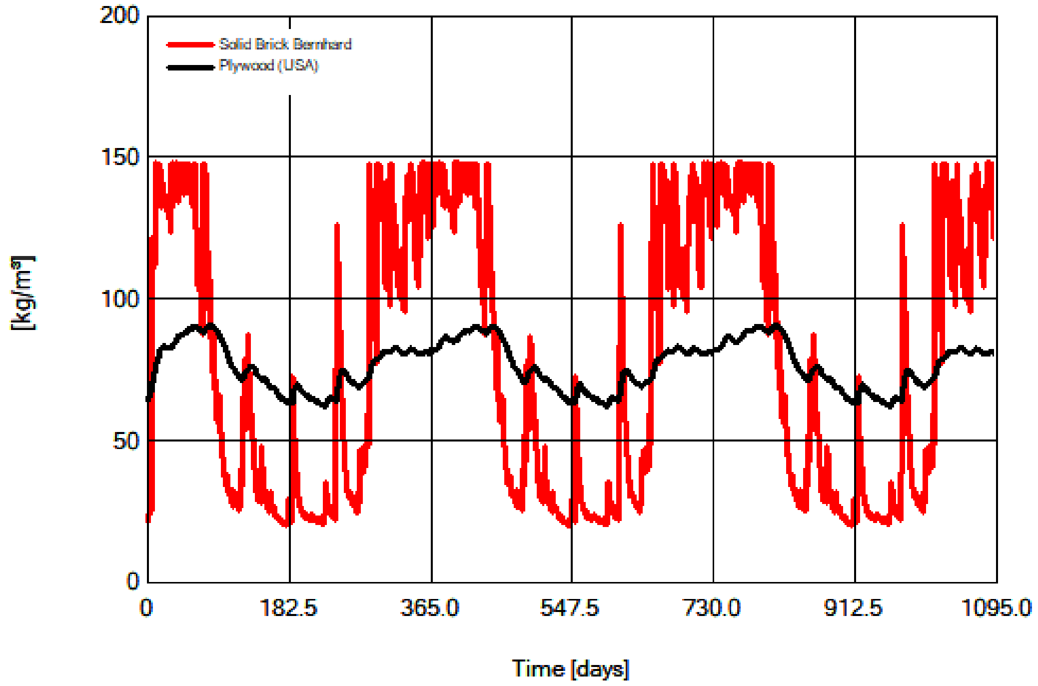
C7: WUFI Graph of Brick Jointed with 1% Zinc Stearate Base Mortar in Cold Year



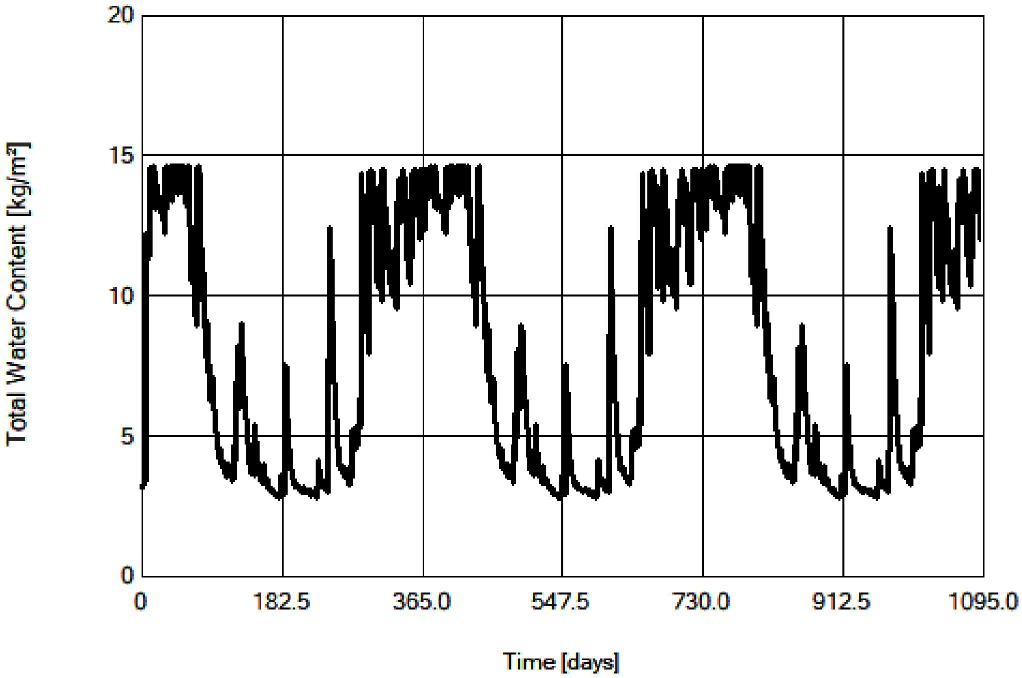


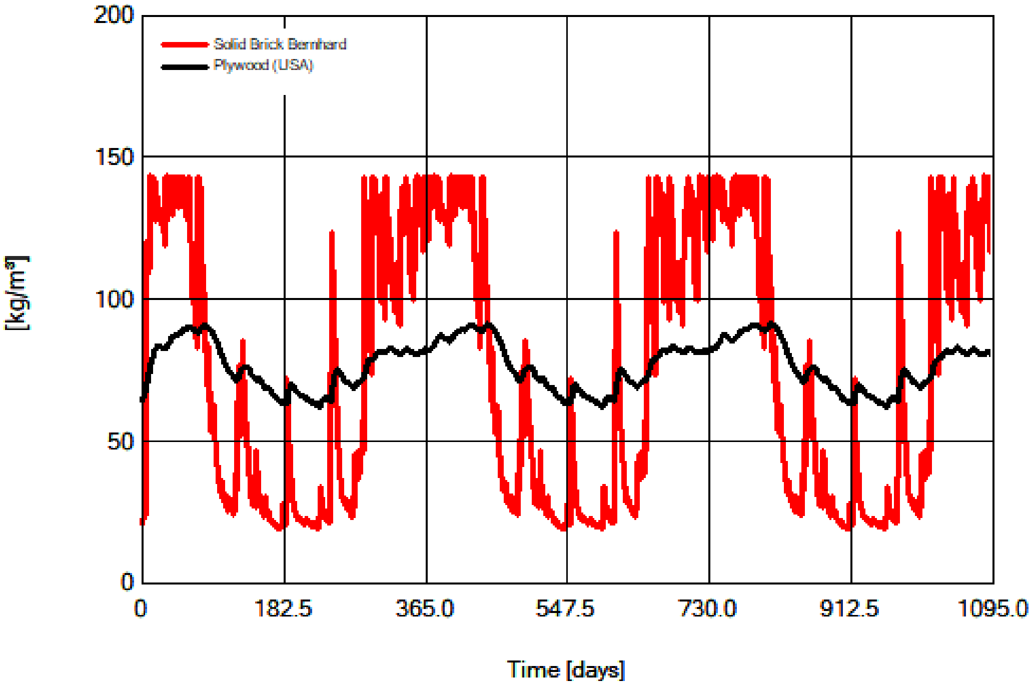
C8: WUFI Graph of Brick Jointed with Base Mortar in Warm Year



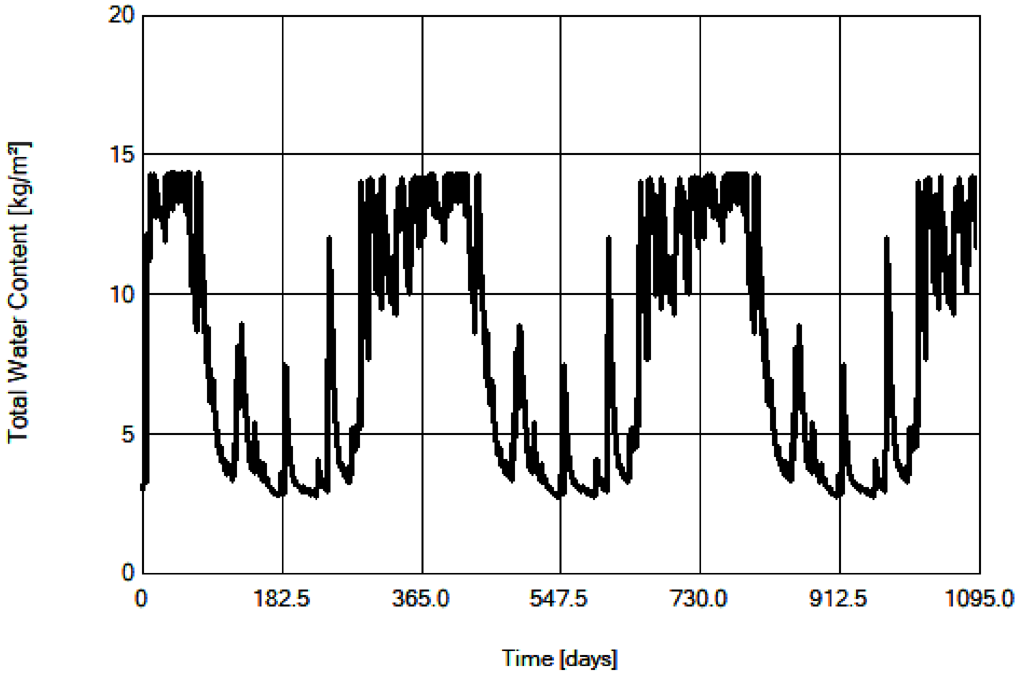


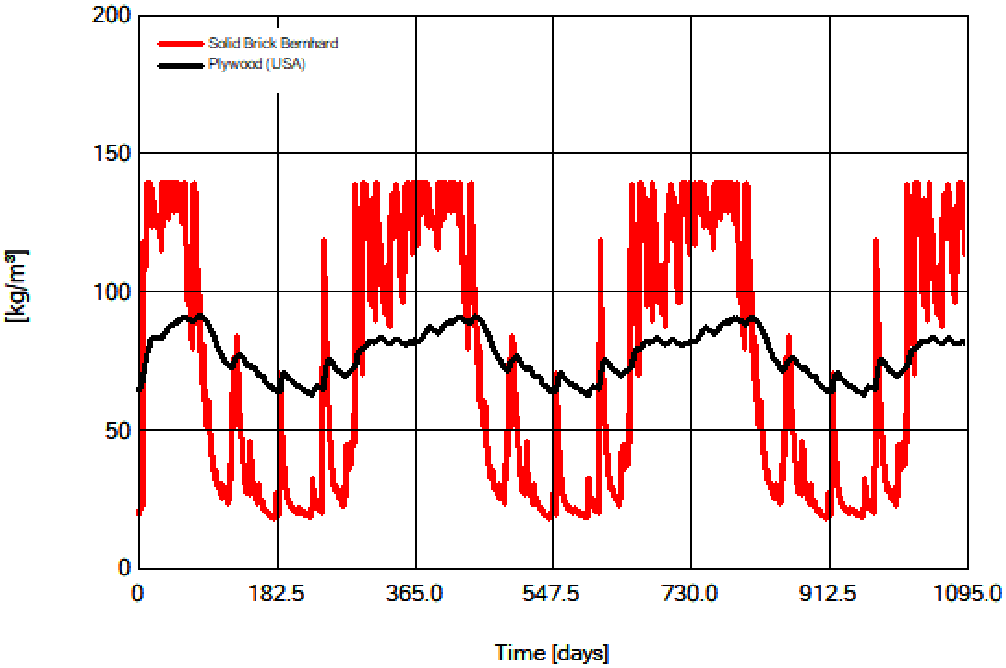
C9: WUFI Graph of Brick Jointed with 0.5% Zinc Stearate Base Mortar in Warm Year



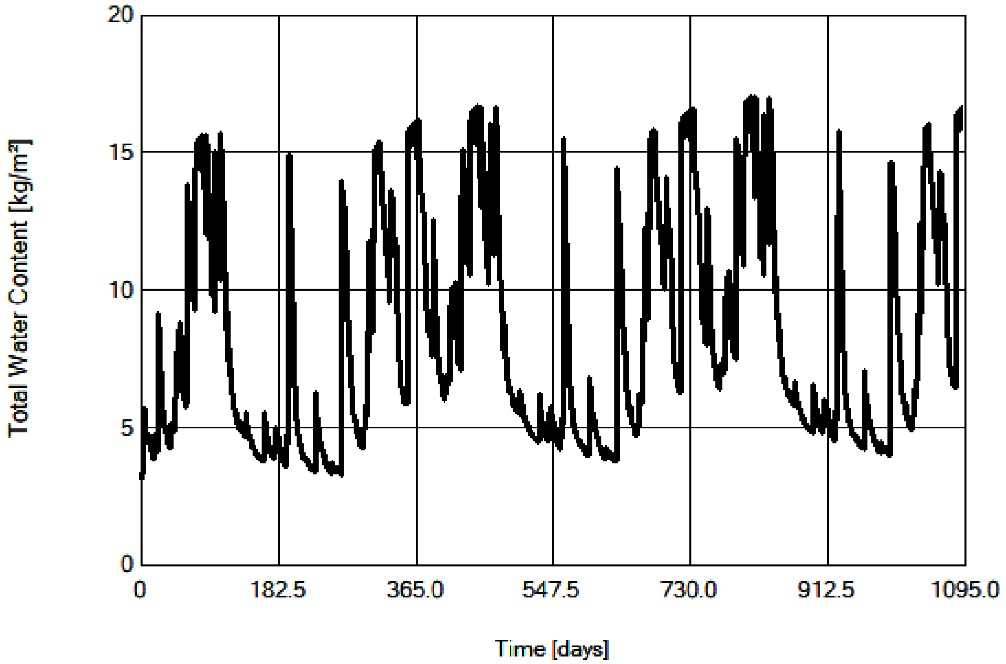


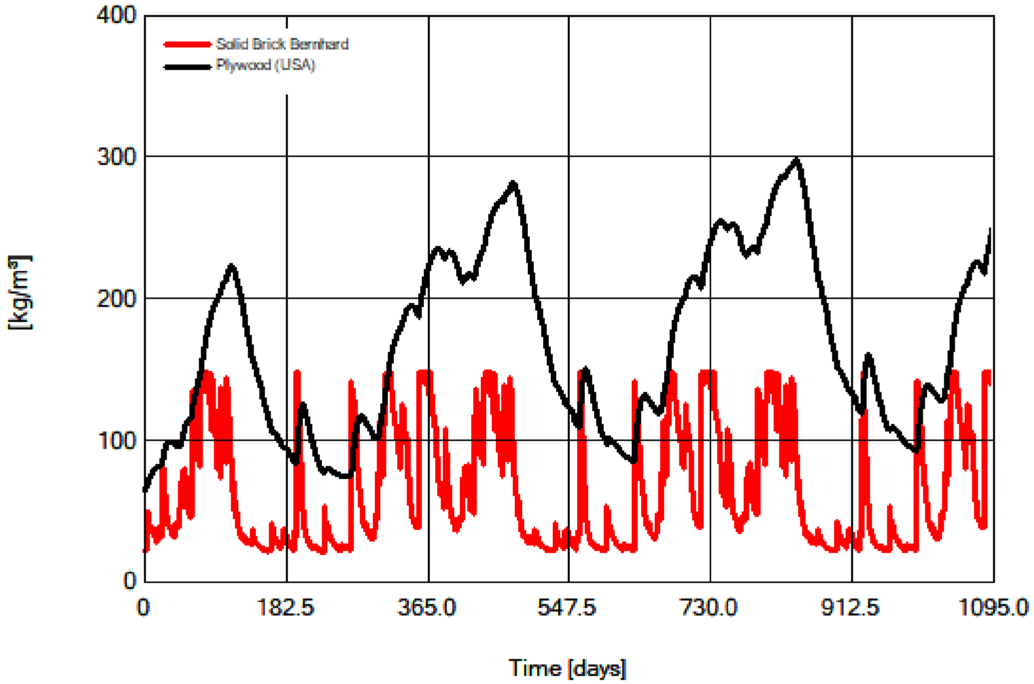
C10: WUFI Graph of Brick Jointed with 1% Zinc Stearate Base Mortar in Warm Year



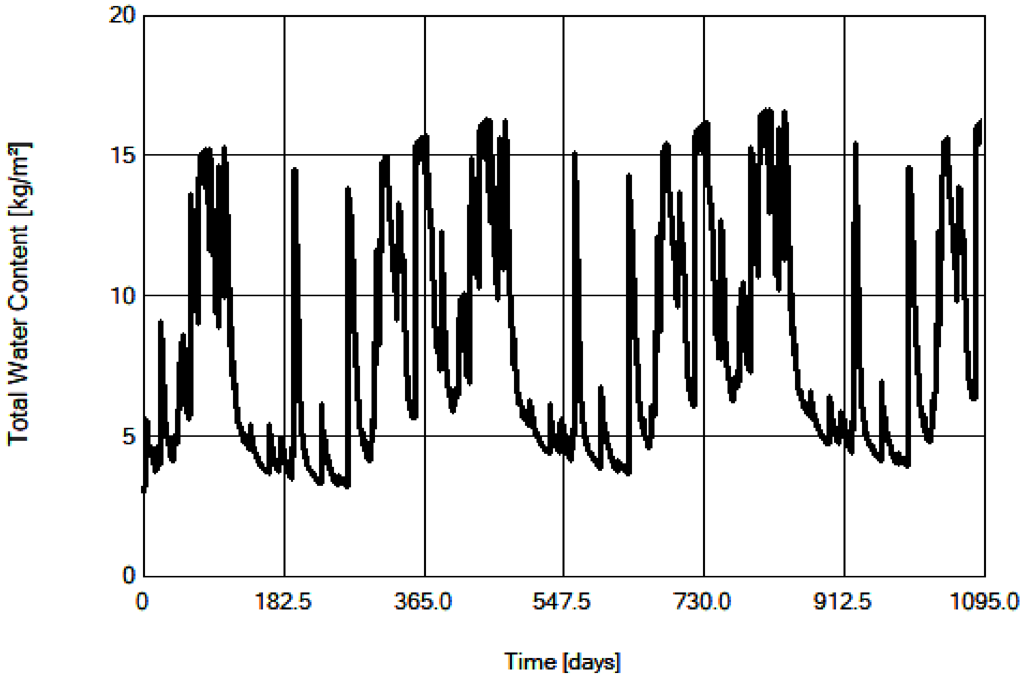


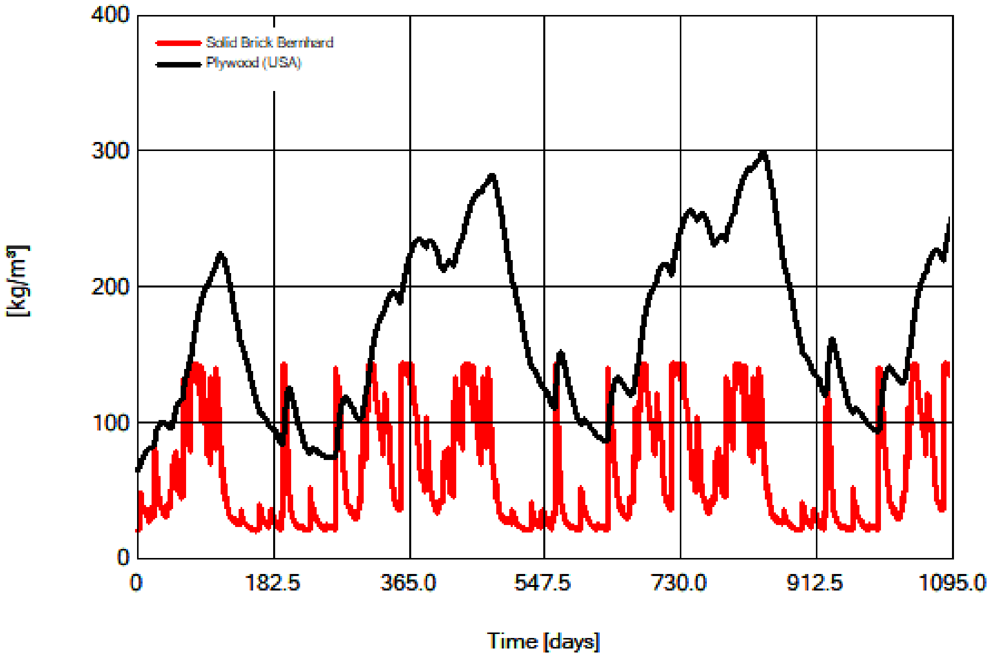
C11: WUFI Graph of Brick Jointed with Base Mortar in Cold Year without Air Cavity





C12: WUFI Graph of Brick Jointed with 0.5% Zinc Stearate Base Mortar in Cold Year without Air Cavity





C13: WUFI Graph of Brick Jointed with 1% Zinc Stearate Base Mortar in Cold Year without Air Cavity