

# **Hygrothermal Performance of Drywall Reinforced with Kraft-Paper Honeycomb in the Canadian Context**

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## **Abstract**

Drywall board-based structures, a competent and cost-effective method of providing flexible partitioning assemblies in commercial and residential houses, are now widely used as walls or ceilings. However, the gypsum-based drywall that has been used in construction is not water-resistant and can create problems such as mold growth and structural defects. The aim of this study is 1) to develop a new sandwich panel with better physical and mechanical properties using locally sourced materials 2) to investigate the long-term hygrothermal performance of the new sandwich panel through using a numerical simulation. The sandwich panel is composed of two different thicknesses of kraft-paper honeycomb core bonded to two cementitious panels with silicone-based adhesive. The experimental results show that the sandwich panel with a thicker core has lower thermal conductivity and higher flexural strength compared to the gypsum-based drywall. The heat and moisture performance of two wall structures were performed using the WUFI Pro simulation program. The results of the modeling analysis present that wall assembly with gypsum-based drywall has higher water content than multilayer sandwich panel. In addition, the multilayer sandwich panel shows a 4.6% lower annual heat flow compared to the reference wall.

**Keywords:** Gypsum-based drywall, sandwich panel, hygrothermal performance, kraft paper honeycomb, flexural strength, water content.

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# CHAPTER 1

## 1. Introduction

### 1.1. Background

In recent years, there has been a growing global concern regarding the environment's possible effects on health problems, construction durability, and energy consumption [1]. Since people spend most of their time (80-95%) indoors, the material selection for construction projects becomes an essential factor in providing thermal comfort and indoor air quality, the most significant parameters in controlling indoor environment quality. Because relative humidity is one of the most important parameters influencing perceived indoor air quality and human comfort, keeping the indoor relative humidity at a very stable level is very important [2,3]. High moisture levels can adversely affect the performance of building envelopes and the occupants' well-being through introducing condensations and mold growth [4,5]. Therefore, the requirement of developing high-quality building materials is necessary to improve building performance in terms of indoor air quality, energy performance, and durability of the building envelope

Since the early "1900s", gypsum and gypsum-derived materials including drywall, have been widely used in building construction for a variety of purposes due to their excellent availability in nature and low energy consumption in manufacturing [6]. Gypsum-based drywall, used for interior walls and ceilings of residential and commercial buildings, offers advantages such as ease of workability, low cost, and fire resistance [7]. However, drywall has poor moisture and water resistance and is susceptible to mold and mildew growth in humid climates [8]. In addition, because gypsum-based drywall disposal in civil structure demolition lacks sufficient support from recycling facilities, it is more common to dispose of drywall waste in landfills. Furthermore, drywall decomposition can result in contaminating both surface and groundwater by increasing the sulfate level in the landfill leachate [7]. As a result, improvements in drywall technology should focus on replacing gypsum-based drywall with functional building materials to improve physical and thermal characteristics while lowering their environmental impact.

Lightweight sandwich technology is being significantly used in both internal and external single-story and multi-story buildings due to its performance and the development of man-made cellular materials as core materials [9]. As fewer people can easily assemble the sandwich panels, their lightweight characteristics can be considered an advantage [10]. In addition, high flexural stiffness, strength, and environmental resistance are the other advantages of sandwich panels [11]. A sandwich panel is made of a thick low-density core layer glued to strong thin faces. The facings are usually made of a stiff, high-strength material. Rigid foam plastics such as polyurethane, and polystyrene are the common core materials due to their low thermal conductivity, low cost, and high moisture resistance. However, foamed plastics are prone to fire hazards and produce intense heat, dense smoke, and toxic fumes [12]. Therefore, the fire performance of sandwich panels can be increased by considering appropriate core materials and facing sheets [12].

In 1956, The United States Forest Products Laboratory investigated sandwich panels manufactured from corrugated paper cores impregnated with low amounts of resin for building applications. Findings presented that the sandwich panels had better mechanical performance (i.e., modulus and strength) compared to the conventional building panels [13]. Many more tests were undertaken in the following years to determine the behavior of sandwich panels with different configurations and types of face and core materials [14]. Moreover, previous literature reviews presented that sandwich constructions have attracted the attention of industry and researchers due to their superior thermal and acoustic characteristics [15]. In addition to the mechanical properties, the hygrothermal performance of the proposed sandwich panel has to be carefully considered to evaluate the effect of moisture transport on overall building envelope performance.

To improve the assembly's performance and durability over its service life, it is beneficial to predict hygrothermal performance using numerical models [16]. Over the last two decades, numerical modeling has proliferated and gained prominence as an effective method for studying the hygrothermal performance of building envelopes with various design configurations in specific climate zones [16]. The majority of hygrothermal tools are the result of various research projects with various goals and objectives. A hygrothermal modeling tool is capable of predicting transient and multi-dimensional heat, air, and moisture (HAM) transport in multi-layer building envelopes. The accurate application of the hygrothermal modeling tool must be verified through theoretical analysis and experimental tests, as these modeling tools are organized around a series of simplified assumptions [16].

This study aims at characterizing mechanical and physical properties, and then the long-term hygrothermal performance of a wall assembly in which the gypsum drywall is replaced by a new sandwich panel made of a Kraft paper honeycomb core layer bonded with two cementitious face sheets. The cementitious mix design contains Portland cement (GU) and flax fibers to enhance tensile strength. Flax fiber has recently attracted considerable attention as a sustainable tensile reinforcement for cement mixtures due to its low environmental impact and high specific mechanical properties [17]. In this study, the One-dimensional (1D) moisture performance simulation model WUFI Pro 6.5 software was selected to investigate the hygrothermal performance of the modified wall assembly against the reference. In addition, the numerical analysis was performed for both wall designs for five consecutive years, ranging from 1<sup>st</sup> January 2016 to 31<sup>st</sup> December 2020. Overall, the kraft-paper honeycomb sandwich panel aims to have lower water permeability, higher strength, better heat and moisture performance than the gypsum-based drywall for residential and commercial applications.

## **1.2. Research Significance and Objectives**

The main objectives of this thesis were: (1) to develop an alternative of kraft paper honeycomb sandwich panel using locally resourced materials to the conventional gypsum-based drywall; (2) to evaluate the hygrothermal performance of a wall assembly that involves kraft-paper honeycomb cementitious sandwich panel compared with conventional gypsum drywall over five consecutive years in the Ottawa region in one-dimensional (1D) moisture performance simulation model of WUFI Pro 6.5. To meet these objectives, multiple steps have been carried out:

1. Developing and characterizing the physical and mechanical properties of the kraft paper honeycomb sandwich panel, including flexural strength, thermal properties, density, water vapor transmission.
2. Modeling two different wall type designs based on the current National Energy Code of Canada for buildings in the Ottawa region. The first wall (reference case) is a conventional wall assembly in Canada with gypsum-based drywall. The second wall is a conventional wall assembly in Canada with a kraft paper honeycomb cementitious sandwich panel.

3. Analyzing the long-term hygrothermal performance of the wall assembly with kraft paper honeycomb sandwich panel including moisture content, relative humidity, condensation and mold growth, and thermal performance, and comparing to the conventional wall assembly with gypsum-based drywall over five consecutive years using WUFI Pro software.

### **1.3. Research Methodology**

This study is performed in three phases; first, to establish the research foundation, a review of the theory and previous research on the topic was conducted followed by experimental testing of the developed sandwich panel. In the experimental section, the physical and mechanical properties of two sandwich panels with two sizes of honeycomb kraft-paper cores were characterized and compared with gypsum-based drywall. In the third phase, a numerical modeling tool of WUFI Pro 6.5 was selected to investigate and compare the long-term moisture performance, humidity levels, mold growth potential, and heat flow of the wall assembly made of kraft-paper honeycomb cementitious sandwich panel with conventional gypsum-based drywall over five years. This one-dimensional analysis investigated the hygrothermal performance of the assemblies by using a range of parameters, including indoor and outdoor climate, indoor relative humidity, the thickness of the selected materials, long-wave radiation, and air exfiltration. For this study, the default WUFI climate file of the cold year within the Ottawa region was selected as an exterior climate for simulation. For the interior climate, the standard of EN 15026, which is possible to include both medium and high moisture load in residential buildings was considered.

### **1.4. Contributions to the body of knowledge**

Previous studies on gypsum-based drywall applications provided a way to improve the physical and thermal properties. However, these analytical and experimental solutions were not applicable for enhancing the mechanical properties. Therefore, a combined approach involving various new materials that can increase both mechanical and hygrothermal properties should be studied. Sandwich structures have become significantly popular in various engineering applications such as building constructions. Many of the previous studies have focused on the sandwich panels with

rigid foamed plastic cores due to the low thermal conductivity and low cost. Also, existing sandwich panels used in construction are mostly focused on non-cementitious materials for the face sheets. However, foamed plastics and non-cementitious materials are generally regarded as dangerous fire materials because they can delaminate and produce huge volumes of toxic fumes. Therefore, this thesis focused on developing a new sandwich panel with kraft paper honeycomb and cementitious faces to improve its physical and mechanical properties.

In terms of numerical simulation, selecting an acceptable and accurate numerical model is challenging in light of recent developments in computer resources. In this study, one-dimensional numerical analysis is performed to evaluate the long-term hygrothermal properties of the wall assemblies. Moreover, numerical modeling is considered to investigate the hygrothermal performance of the wall assembly by replacing the gypsum drywall with the developed sandwich panel.

## **1.5. Thesis Outline**

The thesis consists of 5 chapters, including chapter 1. Both chapters 3 and 4 are written in a journal format. The contents of each chapter are summarized below:

- Chapter 1 provides a general introduction to the research's motivation as well as the objectives and scope of the work.
- Chapter 2 contains the research works that have previously been conducted regarding wall assemblies' functions, properties of drywall and sandwich panels, and previous studies on modeling approaches in determining the hygrothermal performance of building assemblies.
- Chapter 3 provides the experimental part of the research which included the development of the sandwich panel, characterizing the thermal, flexural, density, and water vapor transmission measurement. This chapter includes a description of the properties of the proposed alternative to the problems of gypsum-based drywall.
- Chapter 4 describes modeling two wall assemblies of gypsum-based drywall and kraft paper honeycomb sandwich structure and evaluating the hygrothermal performance of the

developed wall design through using one-dimensional modeling software over consecutive five years.

- Chapter 5 provides the key findings and conclusions of the study and summarizes the limitations and recommendations for future research.

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## CHAPTER 2

### **2. Literature Review**

#### **2.1. Building Envelope**

The building envelope is a physical barrier between the interior and exterior environments of a building [1]. It was defined by Watt (1999) as an enclosure that “buffers or filters external conditions for internal needs” [2]. The elements conventionally associated with building envelopes are floors, roofs, walls, windows, doors, and any other penetrations [1].

Wind, rain, heat and cold, visibility and irradiation protection, providing structural support and strength against internal and external loads, sound control, Fire safety, and security are the main functions of a building envelope [3]. Furthermore, some factors such as building location, function, codes, patterns, climate, and availability of materials and resources can significantly influence the building envelope design and construction [1]. The building envelope definition and functions are shown in figure 2.1.

Given that today's main features in building design are low energy consumption in building systems, durability, and flexibility of building styles, the building envelopes are responsible for protecting the interior of buildings and occupants from environmental effects such as outside temperature fluctuations, humidity, sound. Therefore, a well-insulated envelope might positively reduce energy consumption and improve thermal performance [2]. Because the building envelope is the most prominent element of a structure, using recyclable materials to construct building elements can make buildings environmentally sustainable.

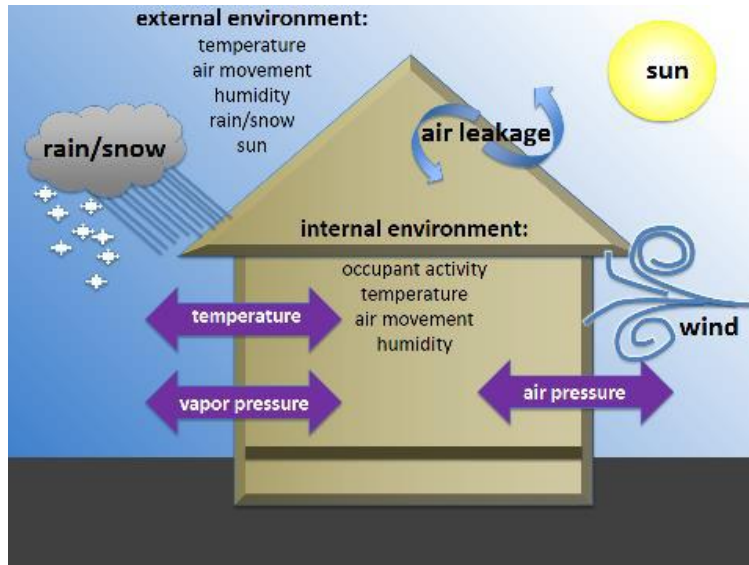


Figure 2.1. Building envelope definition and functions [2].

### 2.1.1. Importance of Hygrothermal Properties in Building Envelopes

Resistance to the passage of moisture and heat, functional performance of the building envelope to the overall performance of the building, is effective in providing an energy-efficient and durable building envelope. To this end, Impermeable materials are used to prevent moisture penetration through water absorption from the ground and rain driven by the prevailing wind [4].

Thermal properties are those physical characteristics of materials, that relate heat transfer to temperature gradients. It is estimated that, of all building components, most of the energy consumption in a building is related to the space-conditioning (heating and cooling). The heat flow through the building enclosure can be controlled by providing adequate insulations against the excessive transfer of heat, resulting in acceptable thermal comfort and energy conservation in buildings.

Health problems and construction durability are closely related to indoor humidity environments. Failure to control the moisture causes damage to the building envelopes as well as increases energy consumption. Therefore, providing an appropriate level of indoor humidity through focusing on the characteristics of building materials should be considered to ensure comfort and sustainability [5].

## **2.2. Hygrothermal Properties of Wood-Frame Walls**

### **2.2.1. Thermal Conductivity**

Measuring the rate of heat flow according to a temperature gradient is called thermal conductivity. Wood can be used as an efficient thermal insulator in buildings due to its low thermal conductivity. Thermal conductivity and specific heat are two principal factors in determining the thermal conductivity of wood. Wood thermal conductivity depends on its density, and thus, wood with higher densities exhibits better insulating properties in comparison with low-density wood. In addition, as the thermal conductivity is related to the moisture content of wood, wood pieces with higher moisture content have a higher thermal conductivity than those with lower moisture content [6].

### **2.2.2. Influence of Structure on Thermal properties**

Although the structure of wood varies with species and types, the Canadian Forestry Service Publication Native Trees of Canada investigated 140 native and commercially important trees. Among them, some are described as coniferous species (or softwood) while the others are deciduous species (or hardwood) [7]. Unlike softwood, the cell structure of hardwood is porous and composed of open-ended vessel elements that form a continuous tube.

The grain structure of wood is an important factor in determining the thermal and moisture characteristics of wood-based materials. In reality, the orientation of wood grain defined as longitudinal (L), tangential (T), and radial (R) is effective on the thermal conductivity of wood (K-value). Figure 2.2 shows the three-grain positioning of longitudinal, tangential, and radial in wood. In longitudinal positioning, thermal conductivity is the highest since the cell walls are continual and the cell cavities are open [8]. However, according to the number of ray cells in hardwood and the ratio of earlywood to latewood in softwoods, the thermal conductivity of tangential is commonly less than that of in radial direction. Fast wood growth of the spring after producing seeds and leaves is defined as earlywood, while, slower wood growth is referred to as latewood [8].

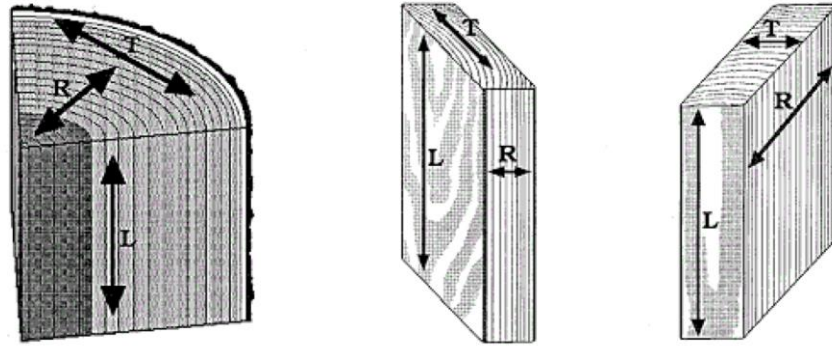


Figure 2.2. The three-grain direction of longitudinal, tangential, and radial in wood [9].

### 2.2.3. Influence of Moisture Content on Thermal Properties

Regarding the relation between thermal conductivity and moisture, it is worth mentioning that woods with higher moisture content have a higher thermal conductivity than woods with lower moisture content [9]. The thermal conductivity of woods with moisture content below 40% can be calculated according to the following equation (1):

$$K = 0.2236 G(1.39 + 0.028 M) + 0.165 \quad (1)$$

Where  $K$  is the thermal conductivity in  $W/m^2 \text{ } ^\circ C \text{ mm}$ ,  $G$  is the density in  $kg/m^3$ , and  $M$  is the percent moisture content. However, for measuring the thermal conductivity of woods with a moisture content of 40% and greater the following equation is recommended (2) [9]:

$$K = 0.2236 G(1.39 + 0.038M) + 0.165 \quad (2)$$

### 2.2.4. Influence of Density on Thermal Properties

Since wood's thermal conductivity is dependent on its density, it can be concluded that wood with higher densities has the minimum insulating effect. In addition, the cell structure and density of wood are effective on its dry density by affecting heat transfer through the presence of air or moisture inside the cells [9]. According to Kollmann, the thermal conductivity of wood in the longitudinal orientation or parallel to the grain can be calculated according to the following equation (3)[9]:

$$K_{ll} = 0.026 + 0.46 + \rho \cdot 10^{-3} \quad (3)$$

Where  $K_{ll}$  is thermal conductivity in the longitudinal direction in  $\text{W/m}^2 \text{ } ^\circ\text{C}$ , and  $\rho$  is the density in  $\text{kg/m}^3$ .

However, for radial positioning or perpendicular to the grain, thermal conductivity can be measured by using the following equation (4) [8]:

$$K = 0.026 + 0.195 + \rho \cdot 10^{-3} \quad (4)$$

### **2.2.5. Influence of Exterior Insulation, Indoor Humidity, and Air Leakage**

Since today's energy-efficient and durable building envelope components are mainly prominent, resistance to the passage of moisture is a functional performance of the building envelope design [4]. Poor construction or unpredicted reactions of building materials can cause many undesirable problems such as wood decay, mold growth, poor indoor air equality, loss of thermal resistance in wet insulation, and damage to building materials from expansion or contraction to the loss of strength.

Depending on the driving forces to the building envelopes moisture can be transferred through the building assembly by two processes of diffusion and air convection. According to Karagiozis and Kumaran, in cold climates, the hygrothermal performance of the walls can be significantly influenced by the vapor permeance of the interior vapor retarder, and by placing a vapor barrier at the warm side of the cavity, vapor diffusion can be effectively controlled [11].

In Canada, installing a vapor barrier of a maximum  $60 \text{ ng (m}^2 \cdot \text{s. Pa)}$  type II water vapor permeance (WVP) on the warm side of the wall assemblies is a code requirement to retard moisture transfer through the mechanism of vapor diffusion [10]. However, air convection, the other moisture transfer mechanism that mainly occurs at joints, holes, and cracks, cannot be prevented by the mentioned code specification [11].

Based on Ojanen and Kumaran's (1996) investigations on the effect of the air exfiltration on the moisture and heat flow in wood-frame buildings, the heat flux will be increased by increasing the airflow rate. Figure 2.3 illustrates the effect of airflow and indoor relative humidity on moisture accumulation.

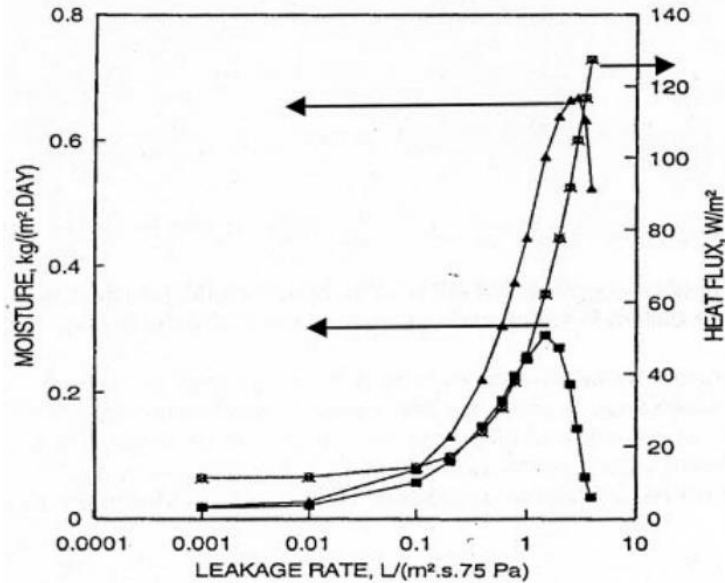


Figure 2.3. The effect of indoor relative humidity on the amount of moisture accumulated within a wall cavity due to air exfiltration [12].

In addition, in terms of water vapor permeance, Ojanen and Kumaran found that the amount of moisture accumulation in the wall cavity will be decreased by increasing the water vapor permeance of the exterior surface and keeping the rate of air exfiltration constant. According to their findings, placing materials with higher vapor permeance to the exterior is functional in tolerating higher air leakage rates [12].

Furthermore, Ojanen and Kumaran (1996) investigated the effect of water vapor permeance of the wall exterior surface and found that as the water vapor permeance of the exterior surface increased, the amount of moisture accumulated in the wall cavity decreased while the rate of air exfiltration remained constant. This study found that when materials with higher vapor permeance are used on the exterior, higher air leakage rates can be tolerated. On the other hand, in another research conducted by Saber et al (2014), it is investigated that the effect of water vapor permeance of outboard insulation on the hygrothermal performance of a wall assembly is dependent on the geographical location of the wall. For example, although the moisture accumulation is increased by increasing the water vapor permeance of the outboard insulation in Vancouver, the effect of water vapor permeance of the outboard insulation is insignificant on moisture retention in Ottawa [12].

### 2.3. Wall Assemblies-Functions and Control Layers

Controlling the heat and moisture flow, infiltrating solar radiation, noise, rain, and providing strength, and rigidity are the main functions of a wall as a part of the building envelope. A perfect wall with the mentioned functions consists of four principal layers according to the importance of the functions depending on the climate and geographic location [13]. Although replacement and configuration of each component may vary according to the climate, A wall assembly's foundation is partly similar in different structures. The simplest typical form of a wall as shown in figure 2.4 consists of the cladding, control layers, and structural components [13].

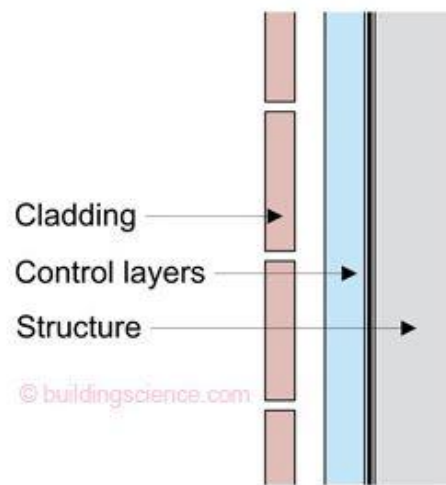


Figure 2.4. The simplest form of a wall design [13].

One of the most effective ways to control the heat flow of building enclosures is to use insulation materials. To this end, considering thermal insulation with airtightness and vapor permeable materials should be considered. Furthermore, using thermal insulation throughout assemblies and providing details to reduce thermal bridging can lead to effective heat flow control in the building envelopes. In multi-unit wood-frame buildings, controlling heat transfer can be achievable by using insulating materials in the opaque wall areas, avoiding thermal bridging, and using thermally efficient window frames and glazing to minimize the conductive losses.

In wood-frame buildings, the heat flow is controlled by considering insulation in stud cavities and attics. Availability, cost, acoustic properties, and thermal performance are effective factors in choosing cavity insulation in wall assemblies. Glass fiber, mineral wool, and cellulose are the most commonly used insulation materials among various existing insulations. As the thermal resistance

of wood is lower than that of insulation materials, heat transfer will occur more through wood studs than through the insulation. Thermal bridging occurs when one part of a wall has significantly higher thermal conductivity than the rest of the wall. Thermal bridging can be reduced by carefully detailing and assembling the insulation. Therefore, the thermal performance of a wall assembly will be increased through decreasing thermal bridging [4].

### **2.3.1. Resistance to Weather and Ground Moisture**

As previously mentioned, controlling the passage of moisture to the inside of the building is a principal function of walls. Moisture, water vapor, and liquid water might penetrate into the wall by absorbing water from the ground, rain, and snow falling on the wall. Exposure of the wall to wind-driven rain and the construction of the wall can have effects on the resistance of the passage of water to the inside face of the wall [4]. Location, sheltering the wall by surrounding buildings or trees are the primary factors in determining the exposure of a wall to protect the building envelopes from rain driven by the prevailing winds [4].

### **2.3.2. Resistance to the Passage of Heat**

Controlling the heat transfer from inside to the outside and outside to the inside is one of the basic factors of walls during periods of cold or hot temperatures to provide a comfortable indoor environment. Walls should provide adequate insulation against excessive heat loss or gain, have adequate thermal storage capacity, and the internal face of walls should be at a reasonable temperature to maintain acceptable and economical conditions of thermal comfort in buildings. [4].

Lightweight materials with low conductivity have more effective performance in preventing heat loss than dense materials with high conductivity. However, dense materials are more appropriate than lightweight materials regarding thermal storage capacity [4]. Figure 2.5 presents the thermal storage in walls.

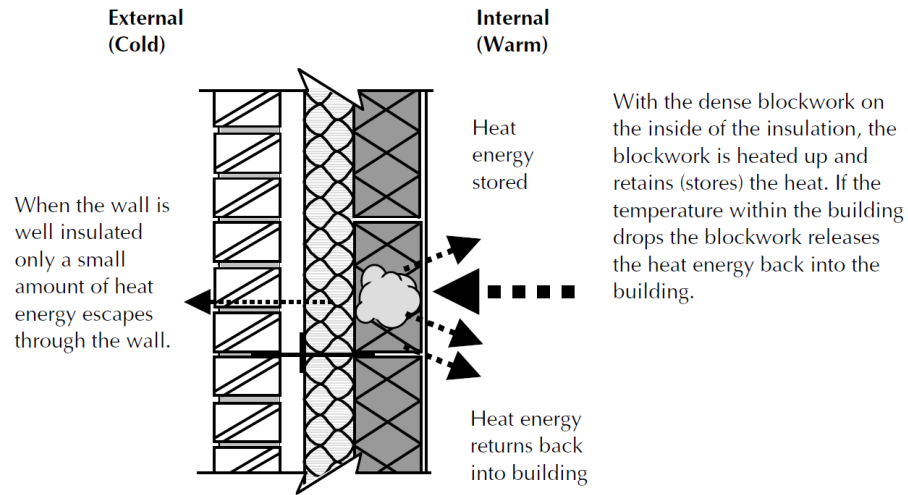


Figure 2.5. Thermal storage in walls [4].

## 2.4. Different Types of Interior Wall Materials

As occupants spend a considerable time within buildings, internal finishes are important in creating a sense of place and in ensuring a healthy indoor environment. Durability, the ability to resist thermal and moisture movement, removing water from the surface that forms as condensation, preventing mold growth are some of the functional requirements of internal finishes [4].

### 2.4.1. Plywood

Plywood, which consists of many sheets of veneer wood glued together, can have effects on increasing durability and minimizing bending. Plywood which is among the more convenient materials for building a wall is an affordable material in saving costs and time. Due to the type of adhesive used in the binding process, plywood is approximately moisture and humidity-resistant. However, low fire resistance and low acoustic properties are the significant problems of using this material.

### **2.4.2. Wood Planks**

Wood Planks, known as cost-effective material, are a remarkable option in achieving a rustic country-style home look. With respect to the installation, although wood planks are not as easy as some other materials, such as veneer plaster, they are installed conveniently. Because wood is readily available in Canada, different types of wood with different sizes and shapes can be selected to achieve the desired look of a wood plank wall. Also, as it is a biodegradable product, it can be considered an environmentally friendly material.

### **2.4.3. Veneer Plaster**

Veneer plaster, a thin layer of wet plaster over a substrate, especially over formulated gypsum board base, is a construction procedure for building interior walls. In terms of advantages, veneer plaster is a harder and more durable surface compared to other materials such as drywall. Also, veneer plaster can be considered an effective water barrier. However, difficult installation and high costs are the disadvantages of this material. In terms of installation, few specialists have the expertise and procedures necessary to correctly place veneer plaster.

### **2.4.4. Drywall Assemblies**

Drywall board, an efficient and cost-effective material in achieving a flexible partition assembly in commercial and residential buildings, is mainly used in interior walls and ceilings in lightweight constructions of Light Steel Framing and Light Timber Framing [14]. These drywall assemblies, a thermal store, and a heat exchanger are one of the most common materials used in North American buildings.

A typical wall assembly consists of steel or wood studs with one or two layers of gypsum boards fixed to each side of the studs. Gypsum is a mineral in crystalline sedimentary rock structures known as calcium sulfate dihydrate  $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ . A core layer of gypsum creates drywall panels with paper-laminated surfaces to provide tensile strength [15]. Figure 2.6 illustrates a construction of a typical wall assembly.

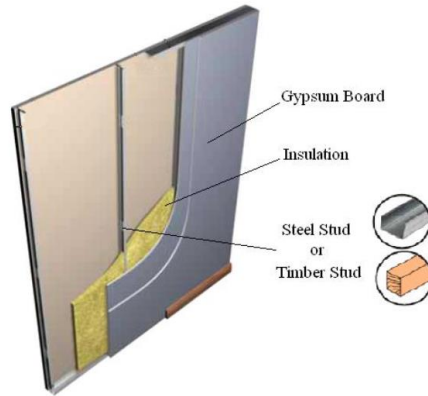


Figure 2.6. A typical drywall assembly [15].

#### 2.4.4.1. Heat Transfer in Drywall Assembly

Figure 2.7 illustrates the heat transfer modes through the drywall system. In drywall assemblies, heat can be transferred through the combination of all three modes of conduction, convection, and radiation. Since drywall is a porous material, heat transfer occurs in modes of conduction through the solid and convection and radiation through the pores from the core to the exposed side of the drywall. According to the Fourier law of conduction, in porous materials such as drywall, heat transfer depends on the effective thermal conductivity. Temperature, density, moisture content, and porosity of the material are the factors affecting the effective thermal conductivity [15].

In addition, in insulated assemblies, since insulation materials are effective in hindering heat transfer through the system, their volume change should be considered a significant element in the analysis of their performance [16].

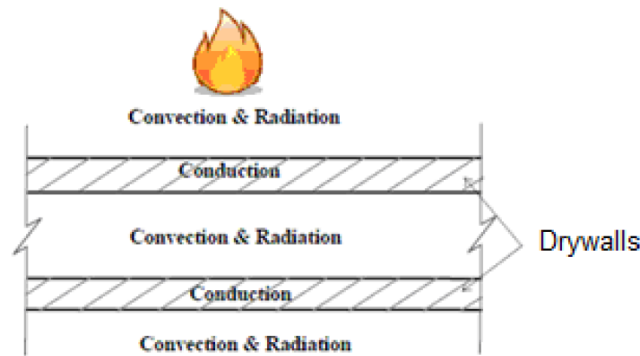


Figure 2.7. Heat transfer modes through drywall system [14].

### 2.4.4.2. Physical Properties of Drywall

Quantifying the thermal properties of drywall at high temperatures is an important factor in evaluating the performance of gypsum used in drywall assemblies. Some of the main physical properties of drywalls as measured by several researchers will be discussed in the following sections [14].

#### 2.4.4.2.1. Specific Heat

Figure 2.8 represents the specific heat of drywall at various temperatures measured by different researchers. The specific heat of gypsum has two peaks, which correspond to the two phases of water dissociation. In addition, a third peak has been reported by some researchers, corresponding to the decomposition of carbonates in gypsum, as proposed by Ghazi Wakili and Hugi (2009). The findings from different studies indicated that the first peak occurs around 100°C. However, the temperature at which the second peak is observed, as well as the values of the peaks, are inconsistent. [15].

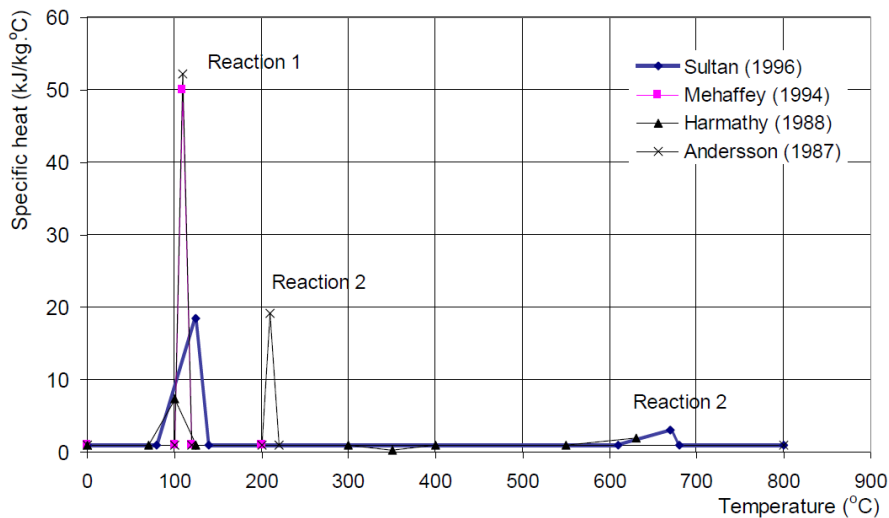


Figure 2.8. Specific heat of drywall boards according to various researchers [15][17].

According to Harmathy's studies (1998), a peak value of 7.32 KJ/kg. °C occurred at 100°C. In addition, a peak of 2 KJ/kg. °C which is considered as a second reaction happened at 630°C [18].

However, Andersson and Jansson (1987) achieved peak amounts of 52.2 KJ/kg. °C at 110°C and 19.2 KJ/kg. °C at 210°C [19].

Mehaffey et al. (1994) provided peak rates of 29KJ/kg. °C at 95°C and 14 KJ/kg. °C at 140°C. Also, Based on Sultan’s investigations, the first peak of 18.5 KJ/kg. °C happened at 125 °C and the second peak of 3.07 KJ/kg. °C occurred at 670 °C [15]. Specific heat at ambient temperature is the principal value to which no reaction occurs. This base value is reported by Harmathy, Mehaffey et al, and Andersson and Jansson to be 0.88 KJ/kg. °C, 0.95 KJ/kg. °C, and 0.7 KJ/kg. °C.

#### 2.4.4.2.2. Thermal Degradation and Density Measurements

Thermogravimetric analysis (TGA) was used by Mehaffey et al. to determine alterations in a mass of 10-30 mg samples of drywall (Type X) with temperature [20]. According to the results shown in figure 2.9, it is obvious that 17.5% of the initial mass is lost between 100 °C to 160 °C. This reduction is related to the first dehydration reaction and the release of water of crystallization ( $0.75 * 21\% = 15.75\%$ ) in addition to the evaporation of free water (less than 3%). Besides, a mass loss at 650 °C which indicates the decomposition of carbonates in gypsum was noticed by Ghazi Wakili and Hugi (2009).

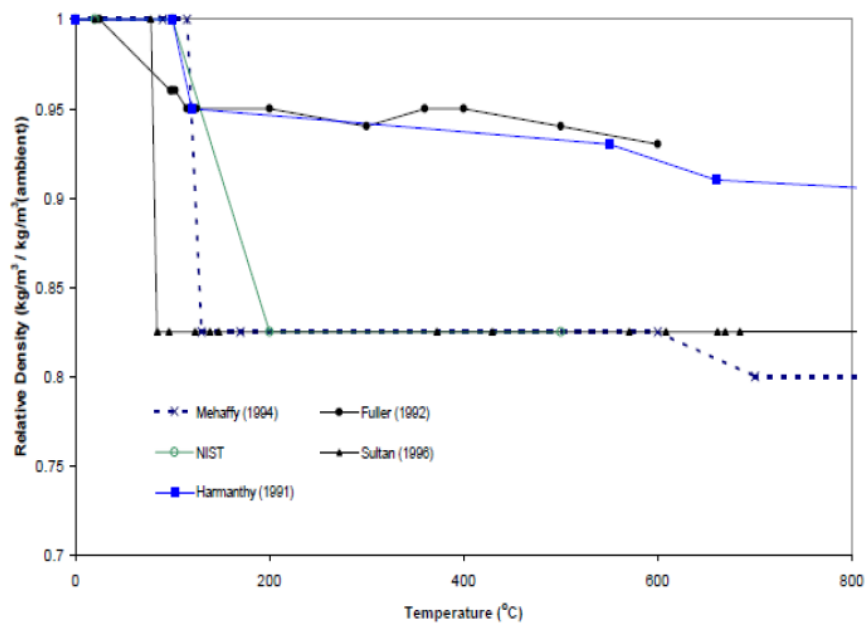


Figure 2.9. The density of drywall board relative to rising temperature [15][17].

The initial density of the 159 mm Type X drywall board as  $648 \text{ kg/m}^3$  was reported by Mehaffey et al [20]. Figure 2.10 shows the mass loss in drywall with rising temperatures. It is worth mentioning that the density of the drywall core of different drywall boards at ambient conditions is dependent on the drywall type and the manufacturers of drywall. Based on Thomas et al' investigations on different samples of Type X drywall boards, the density of 12.5 mm and 15.8 mm boards varies greatly both within and between manufacturers [17]. In various researches, the mean value of the density ranges from  $678 \text{ kg/m}^3$  to  $811 \text{ kg/m}^3$ .

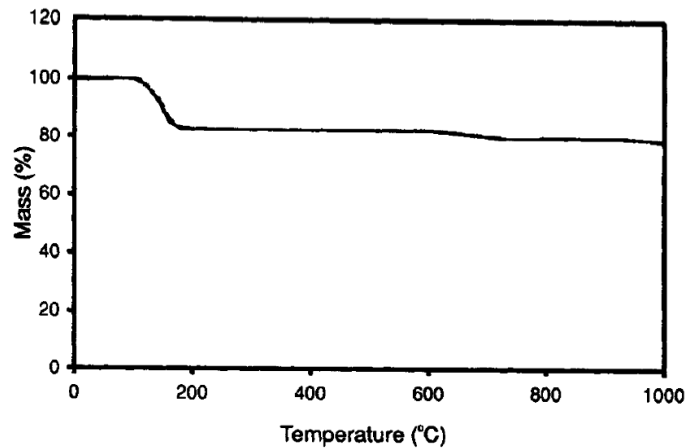


Figure 2.10. Mass loss in drywall with rising temperatures [20].

#### 2.4.4.2.3. Thermal Conductivity

The thermal conductivity of drywall is considered a complicated measurement due to the influences of moisture and radiation in the pores [17]. Microstructure and procedures of measuring the thermal conductivity of drywalls from various sources and manufacturers are different. Although thermal conductivity values provided by different studies vary widely at a temperature above  $500 \text{ }^\circ\text{C}$ , they follow a similar trend at other temperatures. Figure 2.11. represents thermal conductivity of drywalls stated by several researchers. Symbols and lineSymbols show measured rates and modified curves using heat transfer models to indicate standardization between numerical and experimental results.

The Transient Hot Strip (THS) method was used by Andersson and Jansson (1987) to measure the metal strip's resistance which is embedded in the material and derives the thermal conductivity of the material. However, a changeable state scanning method with comparatively small temperature

gradients was used by Harmathy (1988). The obtained findings significantly agree with Mehaffey et al's who employed a TC-31 thermal conductivity meter [20].

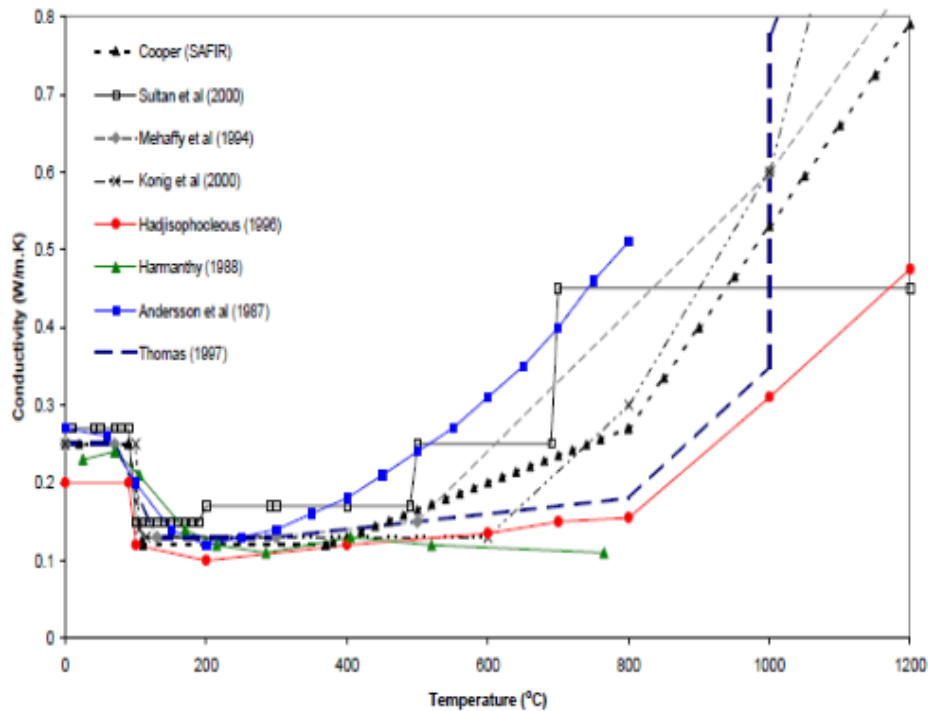


Figure 2.11. Thermal conductivity of drywall board versus temperature [15][17].

Thomas (2002) believes that the opening of cracks and erosion of drywall are achieved due to the remarkable rise in the thermal conductivity of drywall at temperatures over 800 °C. Whereas, the testing method used by Mehaffey et al. prevented cracks from opening up in the board [17]. Despite the variety of information presented by various researchers, all believe that thermal conductivity does not change significantly before the first dehydration reaction starts. This fact can be justified by considering two effects of “1. thermal conductivity at a certain moisture content increases with temperature rise (Parrott and Stuckes, 1975), 2. Overall moisture content of gypsum decreases with temperature rise”. Therefore, Wang (1995) concluded that the thermal conductivity of drywalls slightly increases with temperature as it loses their water. In addition, although the thermal conductivity of drywall reduces at around the temperature of water evaporation, it remains uncertain after water evaporation and at higher temperatures [15].

### 2.4.4.3. Advantages and Disadvantages of Drywalls

Although gypsum boards can be considered as a reasonably cheap, and fire-resistant barrier and soundproof material in the construction of residential and commercial buildings, they have poor water resistance and are susceptible to mold growth in humid climates. Figure 2.12 illustrates the fungal growth on indoor drywall material. Furthermore, gypsum-based drywall disposal in the deconstruction of civil structures lacks proper support from recycling facilities and it is more common to dispose of drywall waste in landfills. The moist anaerobic conditions of the landfill can have effects on occurring anaerobic microorganisms (sulfate-reducing bacteria) in drywall components. Drywalls disposal in landfills can result in adverse environmental impacts due to a series of biological and chemical reactions. When drywall in a landfill becomes wet, some of the gypsum's sulfate dissolves into the water. Therefore, drywall decomposition can result in contaminating both surface and groundwater by increasing the sulfate content in the landfill leachate. Therefore, annual drywall loss due to microbiological damage in the building industry remains a problem [21].



Figure 2.12. Fungal growth on indoor drywall material [22].

According to Menetrez et al (2007), although drywalls have different categories with various lengths and thicknesses, these variations in the type of gypsum have little effect on mold growth. However, he investigated that there are some new innovative categories of drywall boards that are water-resistant and more effective in preventing fungal growth. Also, it is worth mentioning that the existence of nutrients and additives in gypsum can support the growth of fungal and make it

more hygroscopic at lower moisture levels [21]. Nonetheless, there is a lack of understanding of indoor microbial composition, and more investigations should be conducted.

#### **2.4.5. History of Sandwich Panels**

Sandwich construction has become significantly popular among all the possible design ideas in high-performance and weight-critical applications where weight constraints are a limiting factor and must be kept to a minimum [23]. This is mostly due to the relatively high strength- and stiffness-to-weight ratios of sandwich panels, making them highly efficient in material consumption. A typical sandwich structure is composed of two stiff and strong faces, a lightweight and thick core, and two faces of adhesive attachment [24]. Sandwich construction is extremely versatile in terms of the various materials and geometries that it can incorporate, allowing for a wide range of mechanical properties [23]. Although the core can be in the form of a continuous geometry such as metallic foam or discretized periodic geometry, such as honeycomb cores, the facings are built of solid materials [25]. In addition, Fire resistance, thermal properties, mechanical requirements, availability, and cost are the important factors in determining the selection of sandwich materials [25].

The concept of sandwich panel technology in combination with wood-based materials can be traced back to World War II when the ‘mosquito aircraft’ developed by the de Havilland Company is reported to have been the first significant structure to utilize a sandwich panel system [26]. In the construction industry, sandwich panels are increasingly used not only in building structures such as roof and wall cladding systems but also as internal walls and ceilings due to their low thermal conductivity, lightweight, and versatile aesthetic properties [23].

##### **2.4.5.1. Common Types of Structural Sandwich Panels**

###### **2.4.5.1.1. Precast Concrete Sandwich Panel**

Precast concrete sandwich panels are made of two reinforced slabs of high-strength concrete and a sound attenuating foam barrier. The major functions of the facing sheets of sandwich panels are to preserve the insulation and meet the immediate handling and imposed loads. The precast concrete sandwich panel can be considered a cladding material due to its extreme strength and durability. Single layers of factory-manufactured precast concrete employed on a building as

cladding effectively provide a weather-resistant external finish. However, sandwich panels, which consist of two layers of precast concrete with insulation in between, are a well-known product. Rigid board stock or batting materials such as foamed polyurethane plastic, polystyrene plastics, mineral fiber, and fiberglass are used as insulating materials. The inner leaf of the sandwich panel may be employed as a load-bearing structural element to support floor units to optimize the cladding system and increase the efficiency of the construction process. However, precast concrete sandwich panels have been used for more than 50 years, and they have some disadvantages. In fact, they can add a lot of dead weight to the building, increasing the structural members' size such as the beams, columns, and foundation [27]. The difficulties associated with shipping and handling, which impact the speed of installation, are also disadvantages of precast concrete panels [27]. Temperature and moisture differentials can occur in sandwich construction due to exposure conditions, and these conditions may have a greater impact on long-term structural performance than imposed loads. [28].

#### **2.4.5.1.2. Glass Fiber Reinforced Polymers**

The glass fiber reinforced polymers composites are constructed of a rigid or soft polyurethane foam core bonded with a layer of resin such as epoxy to the two layers of fiber Glass (GFRP). Composite GFRP sandwich panels have been used in building applications since 1970. They are quite durable and considerably lighter than concrete panels [29]. In addition, the GFRP layers are effective in withstanding tensile and compressive stresses caused by flexural stresses due to the wind loading caused by pressure or suction. The polyurethane foam core resists shear stresses and contributes to the panel's moment of inertia by acting as a spacer to keep the GFRP skins at the desired distance apart. Furthermore, glass fiber reinforced polymers sandwich panels provide thermal insulation in cladding applications [27].

#### **2.4.5.1.3. Plywood Sandwich Panels**

Plywood can be considered an excellent facing material of sandwich structures. The sandwich panels composed of plywood are lightweight and provide high strength. Furthermore, plywood sandwich panels offer some advantages of being easily finished, dimensionally stable, and repairable if broken. The plywood sandwich panel's core can be made of polystyrene foams and

paper honeycomb by considering the core material's resistance to shearing pressures, heat and vapor transmission, and degradation by heat and moisture [28].

#### 2.4.5.1.4. Honeycomb Sandwich Structures

##### 2.4.5.1.4.1. Honeycomb Panel Construction

The honeycomb sandwich panel is made of two high-rigidity-facing sheets bonded to a low-density honeycomb. A honeycomb sandwich panel is a functional structure that increases the strength and stiffness to weight ratio of a system having such structures. This is not only because of the existence of the core but also due to the facing sheets. Figure 2.13 represents a honeycomb panel construction [30]. By varying the core thickness and the face sheet's material, different characteristics and desired performance, especially the high strength-to-weight ratio, can be obtained [31].

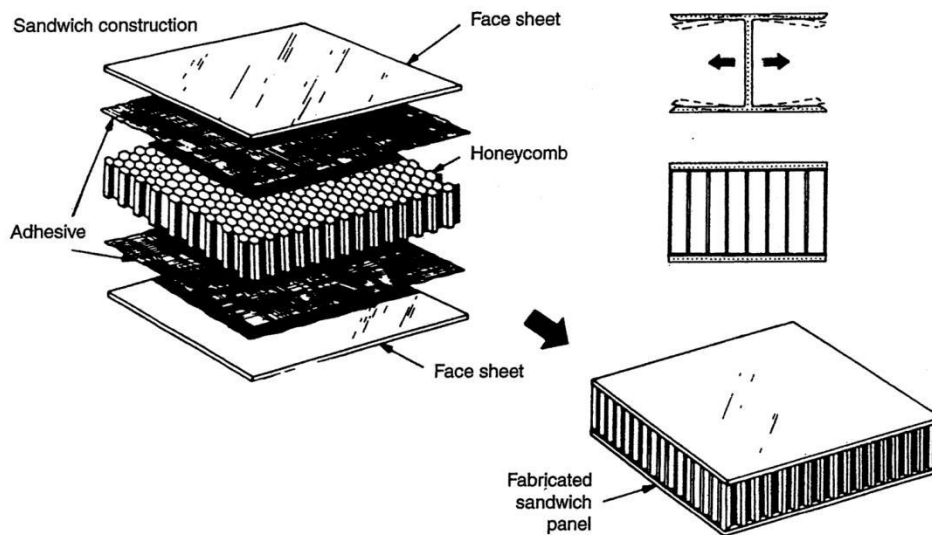


Fig 2.13. Honeycomb panel construction [30].

##### 2.4.5.1.4.2. Honeycomb Cell Positioning

Although Different configurations of hexagonal, reinforced hexagonal, overexpanded (OX), square, flex-core, spirally wrapped (Tubecore), and cross core can be considered for honeycomb structures based on the application, a hexagon as shown in figure 2.14 is more productive than other types. In addition, according to figure 2.15, the reinforced hexagon has influences on

improving mechanical properties due to the existence of a reinforcing layer between the hexagon [32].

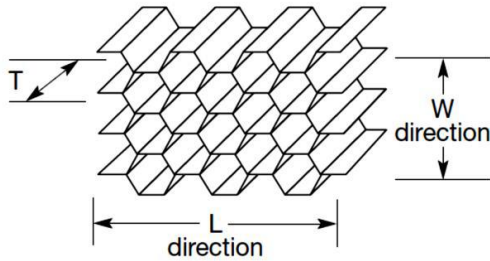


Fig 2.14. Hexagon honeycomb [32].

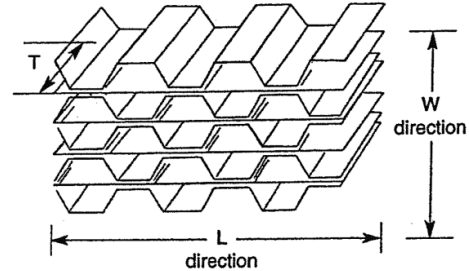


Fig 2.15. Reinforced hexagon honeycomb [32].

According to figure 2.16, the over-expanded (OX) honeycomb is appropriate for improving the longitudinal shear properties of a regular hexagonal honeycomb due to its expansion in width or transversal direction. Figure 2.17 illustrates the flex-core configuration. The flex-core honeycomb, which is suitable for curved structures provides higher shear strength in comparison to a hexagon honeycomb of equivalent density [32].

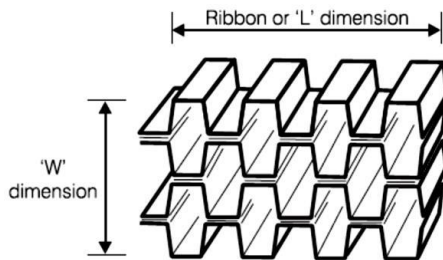


Fig 2.16. Over expanded (OX) configuration [32].

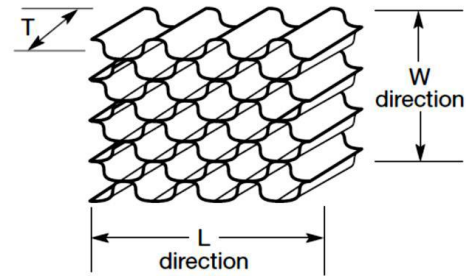


Fig 2.17. Flex-core configuration [32].

Tube-core and cross-core configurations shown in figures 2.18 and 2.19 are designed for energy absorption for a small column or a cylinder in a space envelope and in multiple directions. Crush strength occurring at the un-supported edges of a standard honeycomb can be reduced by considering a tube-core honeycomb [32].

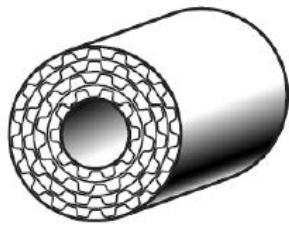


Fig 2.18. Tube core configuration [32].

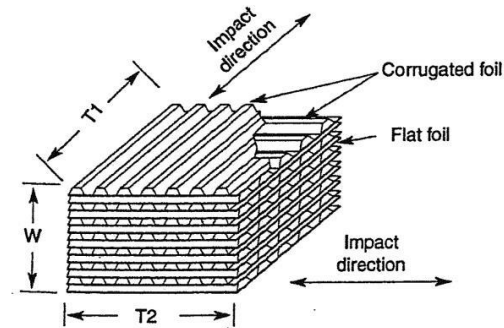


Fig 2.19. Cross-core configuration [32].

### 2.4.5.1.4.3. Honeycomb Materials and Properties

Honeycomb materials are divided into two groups of non-metallic and metallic. Materials such as kraft-paper, thermoplastics, aramid fiber, fiberglass, carbon, and ceramic are considered non-metallic honeycombs. Steel and aluminum are examples of metallic honeycombs. Table 2.1 shows some of the sandwiches which are commonly used in buildings [33].

Table 2.1. Typical structural sandwich panels for buildings [33].

Type	Core		Structural facing		Additional
	Thickness(mm)	Material	Thickness(mm)	Material	Facing
1	76	Paper honeycomb	0.6	Aluminum	None
2	76	Paper honeycomb and plastic foam	0.5	Steel	None
3	51	Aluminum honeycomb	1.6	High pressure laminate	None
4	76	Paper honeycomb	3.6	FRP	Gypsum board
5	56	Plastic foam <sup>1</sup>	3.2	Cement asbestos board	Gypsum board
6	89	Corrugated FRP <sup>2</sup>	2.5	FRP	None

<sup>1</sup> This panel has structural aluminum plastic.

<sup>2</sup> FRP indicated fiberglass reinforced plastic.

The most common material for structural sandwich panels for buildings is kraft paper. kraft paper is produced in various weights and thicknesses and is cheaper rather than other materials used for a honeycomb structure. Impregnating kraft paper material with resin improves both dry and wet

strength and kraft paper honeycomb resistance against water. Different characteristics of kraft paper's weight, amount and type of resin impregnation, and cell size are effective in determining the mechanical properties and cost of kraft paper honeycomb. Furthermore, this material can be used as thermal insulation through filling the cell with polyurethane or phenolic resin [33].

## **2.5. Modeling Approaches**

Heat, air, and moisture (HAM) analysis methods can range widely in terms of comprehensive computer models that comprise transient heat, vapor, liquid, and air transfer with different material properties and complete descriptions of phenomena such as wind-driven rain. Therefore, many studies investigated the hygrothermal performance of several walls and its impact on indoor conditions numerically [34].

In research conducted by Ojanen and Kumaran (1992) a finite-difference technique was used to solve the transient heat, air, and moisture transfer in two-dimensional multilayer building components and evaluate the moisture performance of the building envelope due to the exfiltration of indoor air. The findings of the study showed that indoor and outdoor climatic conditions and the air exfiltration rate are the essential factors in determining the moisture accumulation within the wall cavity. In reality, in situations where indoor and outdoor climatic conditions allow moisture accumulation, high moisture contents in wall assembly are obtained through any small air exfiltration rates [12].

Saber *et al.* (2014) further investigated the hygrothermal performance of wood frame wall assemblies using a two-dimensional hygrothermal model (hygIRC-C), developed by the National Research Council Canada (NRC). The findings based on the simulation showed that the most moisture accumulation based on the considered air leakage path happened at the top and bottom portions of the wall assembly. In addition, the results illustrate that the possibility of mold growth in walls constructed using a nominal 38 mm × 89 mm (2 × 4 in.) was lower in comparison to the walls constructed with a nominal 38 mm × 140 mm (2 × 6 in.) studs [34].

Moreover, Glass (2013) investigated the moisture performance of residential wood-frame wall assemblies using a one-dimensional transient hygrothermal modeling software WUFI Pro 5.1. In this research, all the assemblies included oriented strand board (OSB) sheathing. The moisture

content and drying potential of oriented strand board (OSB) sheathing were investigated for a variety of parameters, including different exterior insulation materials, air exfiltration rates, wind-driven rain, and wall orientations. He found that the drying potential of the sheathing is significantly dependent on the wall orientation, the type, and the vapor permeability of exterior insulation [34].

## **2.6. Identifying Research Gap**

The majority of existing honeycomb sandwich panels using in construction are constructed of non-cementitious materials such as ceramic, aluminum, and wood for the sheathing and there is a limited number of studies focused on the cementitious panels as facing sheets. Therefore, more research is required focusing on the cementitious boards to improve the thermal and mechanical performance of sandwich panels compared to the conventional gypsum-based drywall.

Furthermore, there is a limited number of Canadian studies that developed kraft-paper honeycomb sandwich panels made of locally resourced materials. Therefore, further research should focus on designing kraft-paper honeycomb sandwich panels based on the Canadian building code requirements.

Finally, yet importantly, there is a need for research to evaluate the long-term hygrothermal performance of the developed kraft-paper honeycomb sandwich panel under Canadian weather conditions with different moisture loads.

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## CHAPTER 3

### 3. Research methodology

#### 3.1. Introduction

The methodology of this thesis is divided into two sections: laboratory experiments and numerical simulation. The main objective of the laboratory experiments was to develop and investigate the physical and mechanical properties of the cemented face sandwich. In this regard, two specimen types were made for flexural and thermal conductivity tests. The specimens were made by adding flax fibers (1% by weight) to GENERAL USE Portland cement. Then, the mixture was poured into molds of two different sizes and two different shapes rectangular and square for testing for flexural and thermal tests, respectively. In the following step, the samples were covered in plastic and cured at room temperature ( $22\pm 1$  °C) for 24 hours before being de-molded. Then the kraft-paper honeycomb core was cut into two sizes to match the footprint of the cementitious flexural and thermal samples. A caulking gun is used to apply the adhesive to the interior face before evenly distributing it with a spatula to achieve a uniform spread, 1 mm in thickness. This was followed by experimental tests to characterize the physical and mechanical properties of the sandwich panels. Some properties such as flexural strength, density, thermal conductivity, and water vapor transmission of the developed sandwich panels were investigated. Figure 3.1 shows the flow chart of the experimental section.

Another goal of the thesis was to investigate the long-term hygrothermal performance of the new sandwich panels and compare them with the gypsum drywall. To achieve that, a numerical analysis was performed using one-dimensional hygrothermal modeling called WUFI Pro. The numerical simulation was performed to evaluate the long-term hygrothermal performance of wall assembly with a developed sandwich panel and compare it to the conventional wall assembly with gypsum drywall. The output includes data on moisture content, relative humidity, mold isopleths, and thermal performance of the designed wall assemblies over the five consecutive years. The flow chart of the numerical simulation is presented in figure 3.2.

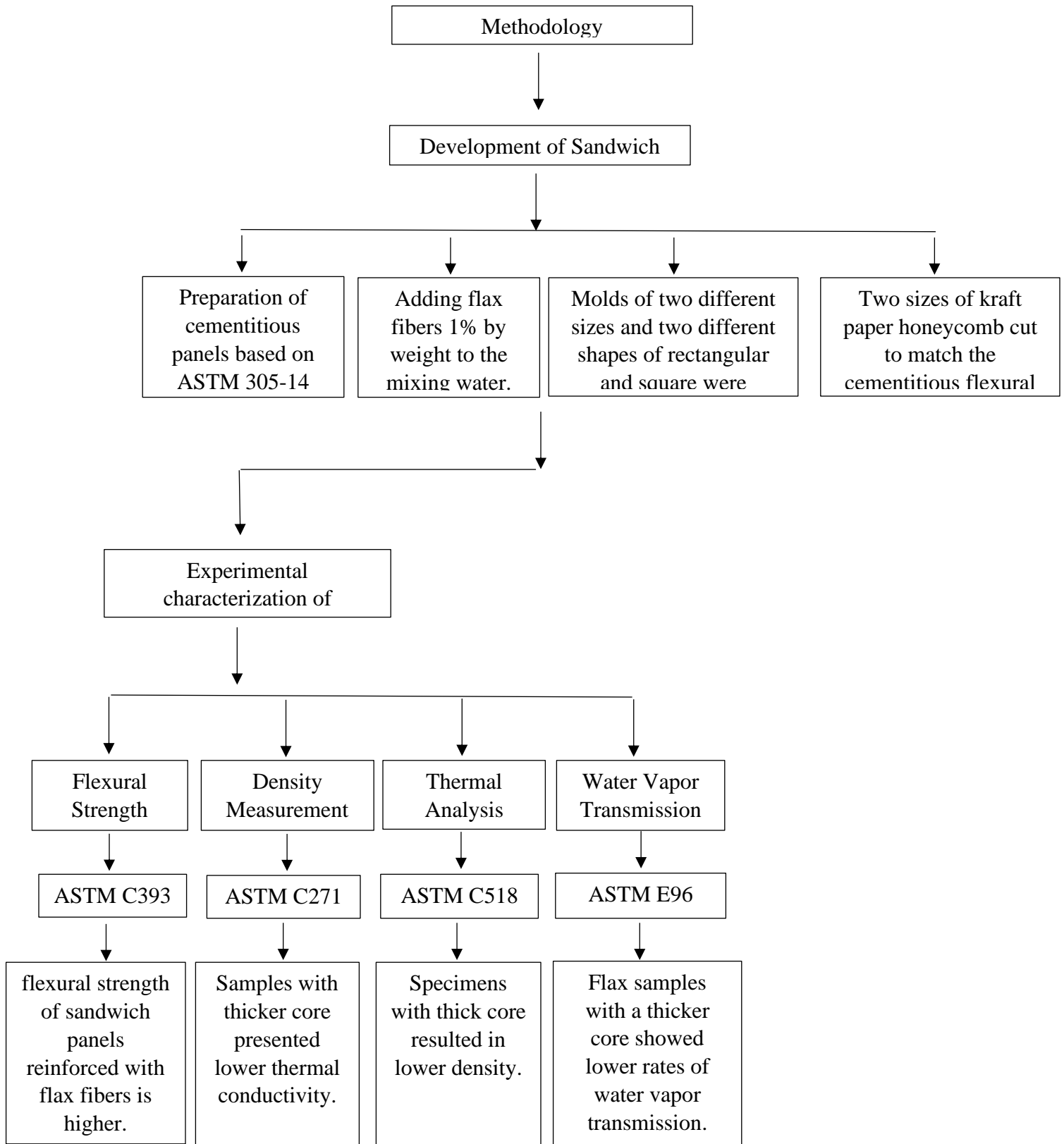


Figure 3.1. The flow chart for the experimental section.

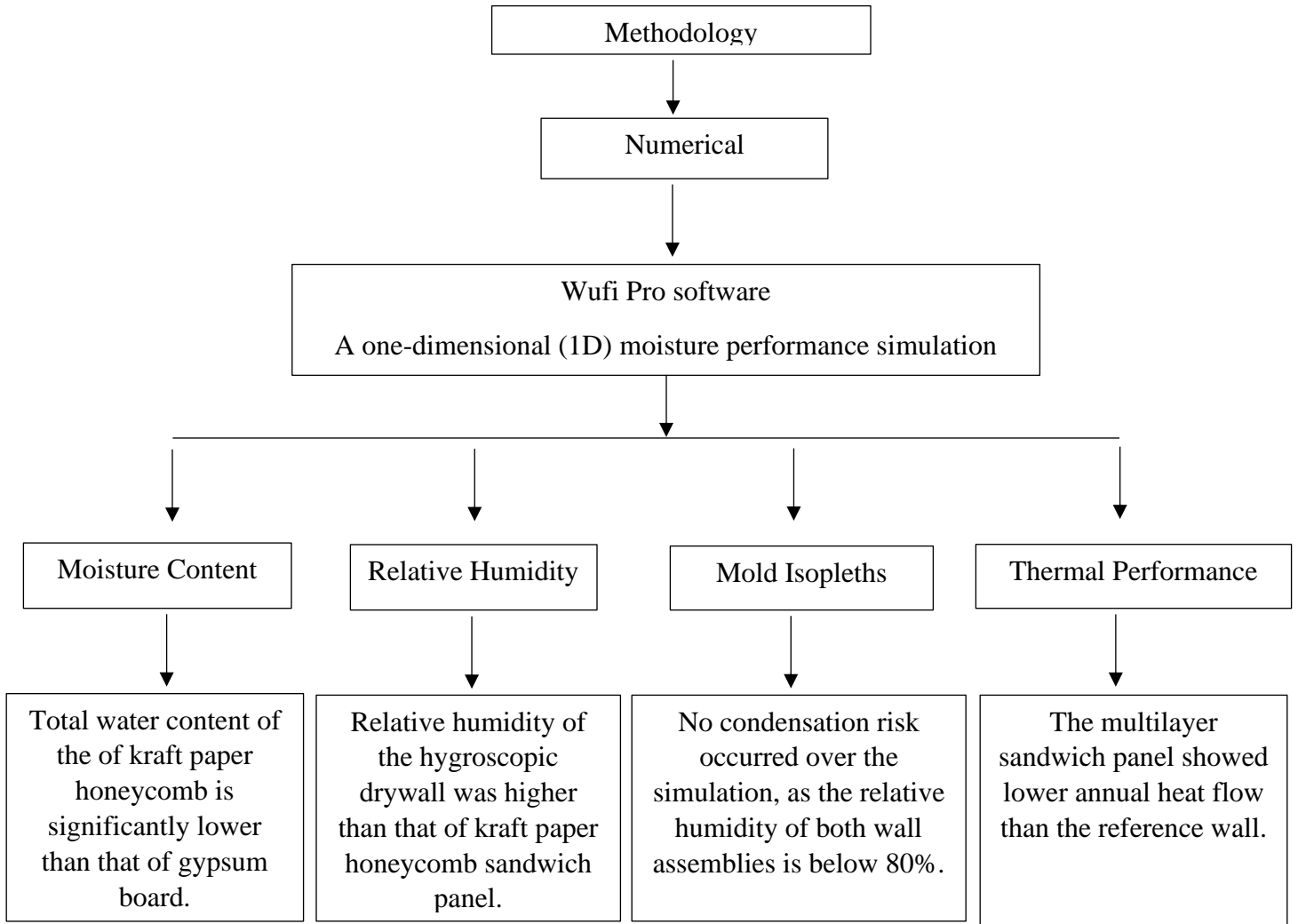


Figure 3.2. The flow chart for the numerical simulation section.

## CHAPTER 4

### **4. Cementitious Insulated Drywall Panels Reinforced with Kraft-Paper Honeycomb Structures**

#### **4.1. Abstract**

Standard building practices commonly use gypsum-based drywall panels on the interior wall and ceiling applications as a partition to protect the components of a wall assembly from moisture and fire to uphold building code and ensure safety standards. Unfortunately, gypsum-based drywall panels have poor resistance to water and are susceptible to mold growth in humid climates. Furthermore, the accumulation of drywall in landfills can result in toxic leachate impacting the surrounding environment. A proposed solution to the pitfalls of gypsum-based drywall arises in its substitution with a new lightweight composite honeycomb sandwich panel. This study aims to develop panels with improvements in flexural strength and thermal insulating properties through the combined use of cementitious binder mix and Kraft paper honeycomb structures. The proposed alternative is created by following standard practices outlined in ASTM C305 to create cement panels and experimenting with admixtures to improve material performance that caters to a drywall panel application. To construct a composite "sandwich panel" assembly, the Kraft paper honeycomb structure is bonded to cured cementitious panels. This study aims to provide an alternative to gypsum-based drywall while enhancing thermal, flexural properties and a lower end-of-life environmental impact. Results indicate that the sample flexural strength was high after 7 days but exhibited superior flexural strength at 28 days while providing a substantial increase in R-value when compared to gypsum-based panels. In addition, the reinforced kraft paper honeycomb with a thick core possesses better thermal conductivity with a reduction of 42%, lesser density, and lower water vapor transmission in comparison to the thin kraft-paper honeycomb sandwich panel.

## 4.2. Introduction

The selection of construction materials has a sizeable cradle-to-grave impact on construction projects. The research and technological development on construction materials aim to reduce costs and improve performance and environmental sustainability. Nevertheless, certain materials such as gypsum-derived materials have remained unchanged. Gypsum has been considered a vital construction material among many designers due to its excellent availability in nature, its technological and ecological properties, and the low energy consumption of manufacturing [1]. Today gypsum and gypsum-derived materials have been extensively used for various purposes, such as drywall, in building construction since the early 1900s [2,3]. Gypsum-based drywall is mainly used for interior walls and ceilings in combination with either Light Steel Framing (LSF) or Light Timber Framing (LTF). A typical wall assembly consists of steel or wood studs with one or two layers of gypsum boards fixed to the stud [4].

The main advantages of gypsum-based drywall are ease of installation, low cost, fire resistance, and availability. However, gypsum-based drywall panels have disadvantages such as high thermal conductivity, low moisture and water resistance, and negative environmental impacts [5]. In this respect, drywall is not best suited for all building applications because it does not offer any notable insulating improvements to the wall assemblies, and it could adversely affect its physical properties [5]. In addition, because drywall is easily compromised by mold and mildew growth in humid climates, in the event of a leak or flood, the lack of adequate moisture and water resistance can negatively affect the indoor air quality of the affected rooms in the building [5]. The environmental disadvantages of drywall panels are related to the insufficient facilities to recycle gypsum-based drywalls. The panels end up in landfills where they disrupt the lifecycle of anaerobic 'microorganisms'. Moreover, drywall panels contaminate both surface and ground water by increasing the sulfate content in the leachate created at landfills [6]. Therefore, advancement in drywall technology should target replacing gypsum-based drywall to improve the physical and thermal properties and create a lesser end-of-life impact on the environment.

Previous studies have shown that gypsum-based drywall's physical properties can be enhanced through various techniques. Adding porous materials such as expanded vermiculite (EV), expanded perlite (EP), and carbon nanomaterials (C-300, C-500, and C-750) to the gypsum-based drywall are effective in improving thermal resistance by decreasing thermal conductivity

[9,10,11]. For example, the thermal conductivity of specimens with porous materials of EV, EP, C-300, C-500, and C-750 was decreased by 30%, 20%, 35%, 36%, and 44%, respectively, compared to the samples without the addition of porous materials [10]. Furthermore, previous findings indicated that diatomite in the gypsum mix, which has a low density and porous structure, could reduce the thermal conductivity values of gypsum composites. Adding diatomite to the mixture presented an increase in porosity, which resulted in a decrease in density and in the coefficient of thermal conductivity. In other words, the thermal insulation performance of composites increased by 63.8%, with the lowest thermal conductivity of 0.497 W/m.K.

Regarding water vapor permeability, gypsum boards mixed with EV and EP improved water resistance compared to gypsum boards with carbon nanomaterials [11]. Furthermore, an alternative plasterboard composed of hemp shiv bonding by lime to the conventional gypsum-based drywall showed a better performance of up to five times with respect to moisture buffering properties than the gypsum-based drywall [12]. Although the hygrothermal behavior was improved, this study revealed the plasterboard showed lower mechanical properties compared to the drywall [12]. Therefore, an integrated approach with other innovative materials that can improve both mechanical and hygrothermal characteristics should be considered.

Sandwich structures have become significantly popular among all the possible design ideas in composite structures due to their high performance, stiffness-to-weight ratio, and energy efficiency [13]. Typical sandwich panels are made of a core layer bonded with two face sheets [14]. While the skins are solid materials, the core can be in the form of continuous geometry such as metallic foam or a discretized periodic geometry, like honeycomb or corrugated cores. Sandwich structures have attracted the attention of industries and researchers primarily because of their higher thermal and acoustical properties [15]. Due to these advantages, sandwich structures are actively used in various engineering applications such as civil, marine, automotive, and civil industries – particularly in building construction of roofs and internal walls [18,19].

Many sandwich panels' cores are made from rigid foam plastics such as polyurethane, polyisocyanurate, and polystyrene because of the low thermal conductivity, high moisture resistance, and low cost [18]. However, foam plastics are frequently considered hazardous fire material, which can delaminate and produce large amounts of smoke, heat, and toxic gases [19]. The sandwich structures' fire performance can be enhanced by considering an adequate core

material and sufficiently restraining the facings [19]. Therefore, it can be concluded that the fundamental relationship between the structural and material parameters and the overall performance of the panel is crucial when developing a structured sandwich panel.

This research study aims to develop an alternative of kraft-paper honeycomb sandwich panel made of high-performance materials to replace gypsum-based drywall. The honeycomb sandwich panel is composed of two high-density external layers bonded to an internal core layer made of a low-density honeycomb material [22,23]. Current honeycomb sandwich panels used in construction mainly focus on using non-cementitious materials for sheathing for the honeycomb structure such as ceramics, aluminum, and wood. Distinctively, this study sheathed the core on the external faces with a cured, cementitious panel – taking a fire-resistant construction approach enforced in the building industry. The cementitious mix design consists of widely available Portland Cement (GU) and flax fibers to improve tensile strength. The use of plant fibers as a sustainable tensile reinforcement for a cement matrix has recently received a lot of attention due to the low environmental impact and high specific mechanical properties [22].

As the application's focus for this material is the residential and commercial interiors, the mix design aims to have low water permeability and higher strength than gypsum-based drywall while remaining highly accessible worldwide. A set of experiments on this material were performed to estimate thermal performance, flexural strength, water vapor transmission, and the density of the sandwich panel. Consequently, this research provides valuable information about the physical and mechanical properties of the new sandwich panel that are required for material characterization and modeling.

### **4.3. Methodology**

#### **4.3.1. Materials**

The cementitious mortar used for the sheathing of the sandwich panel was cast from GENERAL USE (GU) Portland Cement. Table 4.1 shows the typical compound compositions of Portland cement. The oilseed flax fibers used for this mix design are sourced from a company based in Saskatchewan, Canada, known as Biolin Research Inc. For the honeycomb core, two thickness alternatives of the kraft-paper-based material were used; 10.16 mm (0.4”) and 19.05 mm (0.75”).

The thickness range was selected to promote future widespread adoption coming from traditional 12.70 mm (0.5”) drywall. Figure 4.1 shows the schematic view of the honeycomb sandwich structure. The honeycomb core is attached to the cementitious specimen using an all-purpose multi-usage silicon-based adhesive from Henkel Canada Corporation that also serves as a barrier for moisture to prolong the service life of the honeycomb core material. Based on data provided by the Tricel company, the source of the kraft paper honeycomb, the paper utilized for manufacturing the honeycomb structure is 85% recycled as well as being 100% recyclable at the end of its service life [23].

Table 4.1. Composition of Portland cement.

Compound	Formula	% By weight
Tricalcium silicate	$C_3S$	55%
Dicalcium silicate	$C_2S$	19%
Tricalcium aluminate	$C_3A$	10%
Tetracalcium aluminoferrite	$C_4AF$	7%

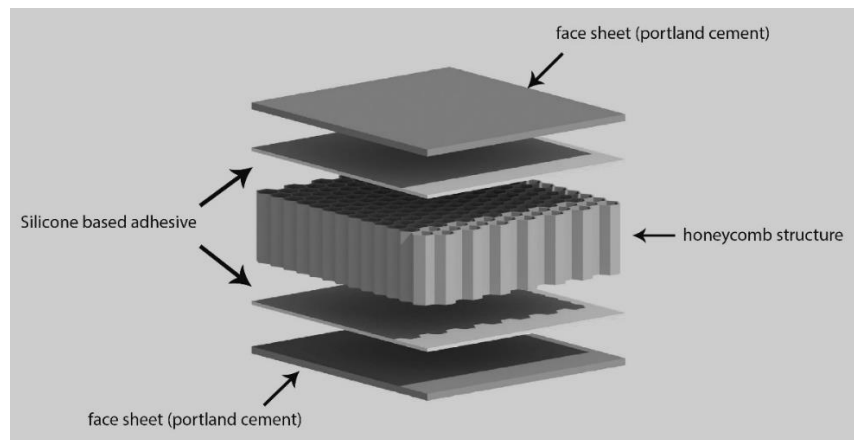


Figure 4.1. The schematic view of the honeycomb sandwich structure.

### 4.3.2. Sample Preparation

The preparation of the cementitious portion of the honeycomb sandwich panels closely follows ASTM305-14 "Standard Practice for Mechanical Mixing of Hydraulic Cement Pastes and Mortars of Plastic Consistency" with minor adjustments for the addition of flax fibers [24]. Firstly, we cut

flax fibers to 10 mm in length to improve their dispersion in the cement paste and add them 1% by weight to the mixing water allowing the fibers to disperse before adding the liquid to the cement powder [22]. Then, using a 0.45 water-cement (w/c) ratio, Portland Cement powder was added without mixing for 30 seconds to allow for the absorption as described by ASTM [21]. Next, the cement paste was mixed at low speed for 30 seconds followed by a stoppage to scrape the bowl/mixer, and finishing with additional mixing for 60 seconds at medium speed.

The mixture is then poured into molds of two different sizes and two different shapes of rectangular and square for testing; 160mm x 40mm x 4mm for flexural and 300mm x 300mm x 4mm for thermal tests, according to ASTM testing procedures for thermal and flexural samples [25]. Air bubbles should be removed to achieve uniformity in the material. Thus, prodding along the edges of the mold in combination with cyclic agitation is used to remove air bubbles. The samples were then covered in plastic and cured at room temperature ( $22\pm 1$  °C) for 24 hours before being de-molded. De-molded samples were left at room temperature for 28 days. The kraft-paper honeycomb material is then cut into two sizes to match the footprint of the cementitious flexural and thermal samples. A caulking gun is used to apply the adhesive to the interior face before evenly distributing it with a spatula to achieve a uniform spread, 1 mm in thickness. Pressing the honeycomb material into the adhesive on both sides completes the honeycomb sandwich panel construction. The samples were cured with uniform pressure under a 1kg weight for 72 hours to ensure even bonding of the adhesive over the sample's surface area. Table 4.2 summarizes the composition of four types of mix designs used for testing.

Table 4.2. Composition of kraft-paper honeycomb samples.

Name	Mix Design	Kraft Paper Honeycomb	Flax Fiber
		Thickness	
		(mm)	(%)
<b>PC<sub>thin</sub></b>	standard Portland Cement	10.16	-
<b>PC<sub>thick</sub></b>	standard Portland Cement	19.05	-
<b>Flax<sub>thin</sub></b>	Flax reinforced Portland Cement	10.16	1
<b>Flax<sub>thick</sub></b>	Flax reinforced Portland Cement	19.05	1

### 4.3.3. Flexural Analysis

A ZwickRoell universal testing machine was used to determine the flexural strength of the panels according to ASTM C393 "Standard Test Method for Core Shear Properties of Sandwich Constructions by Beam Flexure" [23]. The flexure test is effective in determining the sandwich flexural stiffness and the core shear strength. Determining the mean flexural strength included testing five honeycomb sandwich panels of each type of  $PC_{thin}$ ,  $PC_{thick}$ ,  $Flax_{thin}$ , and  $Flax_{thick}$ . In the application of this study, the flexural test was conducted as the most conventional loads exerted on drywall are flexural loads. The Core Shear Properties of Sandwich Constructions were calculated according to the following equation (5) [25]:

$$\tau = \frac{P}{(d+c)b} \quad (5)$$

Where  $\tau$  is the core shear stress of the sandwich panel (MPa),  $P$  is load (N),  $d$  is the sandwich thickness (mm),  $c$  is the core thickness (mm), and  $b$  is the sandwich width (mm).

### 4.3.4. Thermal Analysis

The heat flow meter, located in an environmentally controlled chamber, is an accurate and widely used procedure for determining the thermal conductivity of large samples under moderate temperature conditions [26]. Two isothermal plate assemblies and one or more heat flux transducers are the main components of the heat flow meter instrument. In this research, the thermal analysis of the sandwich panels was determined by a TA Instruments Fox 314 Heat Flow Meter Apparatus (HFMA) according to international standards of ASTM C518 "Standard Test Method for Steady-State Thermal Transmission Properties by means of the Heat Flow Meter Apparatus" [27]. This instrument is accurate for temperatures ranging from  $-20^{\circ}\text{C}$  to  $75^{\circ}\text{C}$  [27]. The specimens were positioned between two parallel plates equipped with heating and cooling systems [27] to provide steady-state and one-dimensional heat flux through the samples by setting plates at constant but different temperatures with an accuracy of  $\pm 0.01^{\circ}\text{C}$  [28]. The thermal conductivity was gauged given the sample thickness as the instrument fluctuated through a range of temperatures [29]. The thermal conductivity of a material in the heat flow meter method is calculated by applying Fourier's law of heat conduction with absolute thermal conductivity accuracy of  $\pm 1\%$  at a mean temperature of plates based on the following equation (6) [30]:

$$K = \frac{Q \times L}{A \times \Delta T} \quad (6)$$

Where  $K$  is the thermal conductivity coefficient of the specimen (W/m. K),  $Q$  is the heat flow rate (W),  $L$  is the distance between the two isothermal panels (m),  $A$  is the surface area of the sample ( $m^2$ ), and  $\Delta T$  is the temperature difference between upper and lower plates (K) [30].

In this study, two samples of kraft-paper honeycomb sandwich panels with different thicknesses were tested to calculate the average thermal conductivity coefficient at different temperatures.

#### 4.3.5. Density Measurement

ASTM C271 "Standard Test Method for Density of Sandwich Core Materials" was used to determine the density of the sandwich-panel core materials [31]. The dimensions were found using a Vernier caliper and a digital scale was used to weigh the samples (in grams) with an accuracy of  $\pm 0.01$ g. To determine the volume of the specimens, plan dimensions and thickness of the samples were measured in millimeters. In this study, different samples of each mix design ( $PC_{thin}$ ,  $PC_{thick}$ ,  $Flax_{thin}$ ,  $Flax_{thick}$ ) were tested to evaluate the average density of each group. The density of sandwich core materials was calculated as follows (7):

$$d = \frac{1\,000\,000\,w}{v} \quad (7)$$

Where  $d$  is density ( $kg/m^3$ ),  $w$  is the final mass (g), and  $v$  is the final volume ( $mm^3$ ).

#### 4.3.6. Water Vapor Transmission

Several experiments on each sample type were carried out according to the ASTM E96/E96M "Standard Test Methods for Water Vapor Transmission Materials" to measure water vapor transmission through permeable and semipermeable materials [32]. Among the applicable methods, the water method is considered for the measurement of permeance [33]. In the water method, the dish impermeable to water or water vapor is filled with distilled water to a level of [19 mm  $\pm$  6 mm] from the sample throughout the experiment. Each of the samples is attached to a dish with a sealant resistant to the passage of water vapor. The dish assembly was placed in a chamber

with a controlled temperature of 23 °C and relative humidity of 50% and then weighed every 24h. The measure of vapor transfer through the sample from the water to the controlled atmosphere can be determined by weighing the sample [34]. After measuring mass change, the water vapor transmission of the samples is calculated as follows (8):

$$WVT = \frac{G}{tA} = \left(\frac{G}{t}\right) A \quad (8)$$

Where WVT is the rate of water vapor transmission (g/h.m<sup>2</sup>), *G* is weight change (from the straight line) (g), *t* is time (h), *G/t* is the slope of the straight line (g/h), *A* is the test area (cup mouth area) (m<sup>2</sup>).

Water vapor permeance which is the water vapor transmission rate of a membrane influenced by unit vapor pressure difference through a unit thickness, can be quantified as following (9) [34]:

$$Permeance = \frac{WVT}{\Delta P} = \frac{WVT}{S(R_1 - R_2)} \quad (9)$$

Where  $\Delta P$  is vapor pressure difference (mm Hg,  $1.333 \times 10^2$  Pa), *S* is saturation vapor pressure at test temperature (mm Hg,  $1.333 \times 10^2$  Pa), *R*<sub>1</sub> is relative humidity at the source expressed as a fraction (in the dish for water method), and *R*<sub>2</sub> is relative humidity at the vapor sink expressed as a fraction.

## 4.4. Results and Discussion

### 4.4.1. Flexural Analysis

Figure 4.2 shows the results obtained from the flexural analysis. A force-deflection graph is displayed to assess the behavior of each sample type; PC<sub>thin</sub>, PC<sub>thick</sub>, Flax<sub>thin</sub>, and Flax<sub>thick</sub> under 3-point bending.

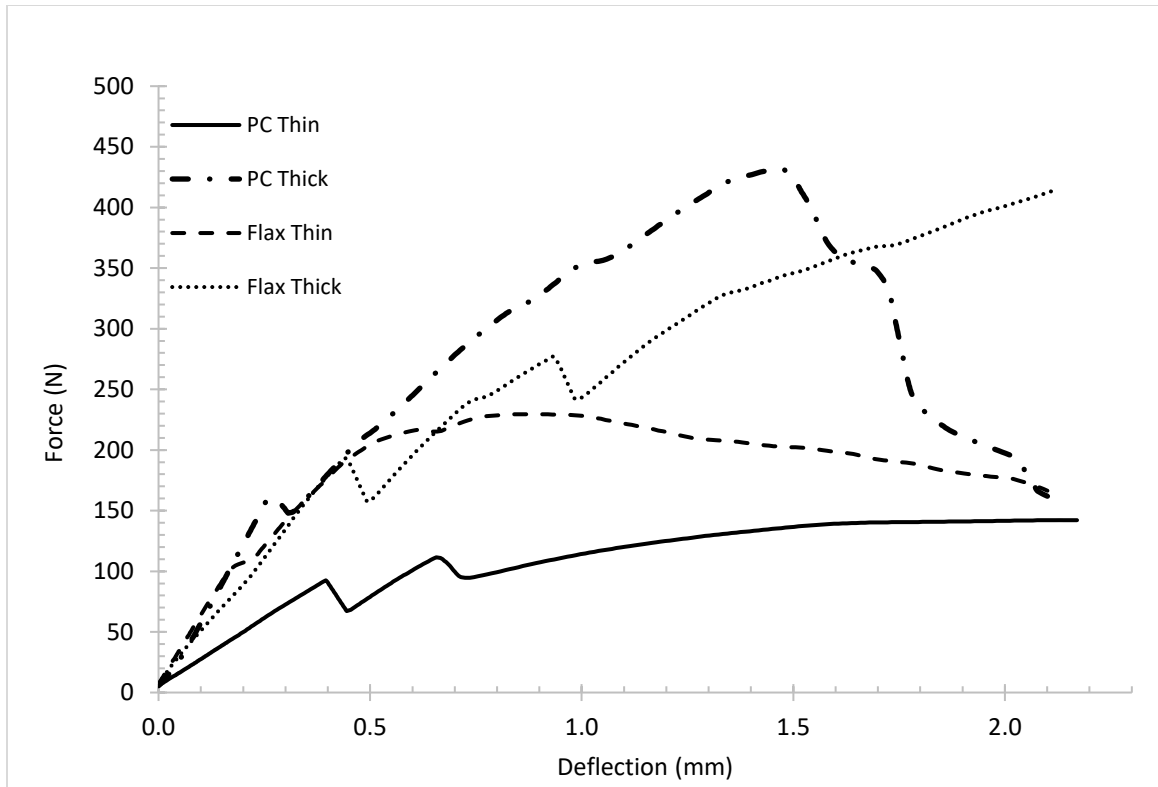


Figure 4.2. Force deflection graph of honeycomb sandwich panels under 3

point bending (Note: only 1 test for each sample is shown based on the avg. peak strength).

The force-deflection graph for 3-point bending indicates a specimen's ability to withstand a force until it reaches the point of failure – where the material can no longer support an increase in load. Abrupt changes in the force of all sample types in the graph signify cracking in the Portland Cement sheathing. The initial slope of the curves before the first crack presented the stiffness of the samples. The findings indicated that  $PC_{thin}$  and  $PC_{thick}$  exhibited early-stage cracking due to the brittle nature of the sheathing. The Portland Cement samples cracked during the gluing and testing stages due to the lack of tensile reinforcement. Furthermore, as the honeycomb sandwich panels are composite materials, the deformation of this material involves both elastic and plastic behavior.

The addition of flax fiber may cause a lack of uniformity throughout samples due to the tendency of fibers to "clump." Nevertheless, the results showed that adding flax fiber increased the 'sample' stiffness compared to the non-flax samples as initial cracks in the samples were prolonged and occurred at higher forces, especially for the  $Flax_{thick}$  sample. All specimens showed decreased

stiffness after cracking, as the force becomes more reliant on the kraft-paper honeycomb. The curved nature of each graph before the failure point indicated its plastic deformation, in which the honeycomb appears to withstand most of the force due to the 2-3 continuous sheath cracks in each specimen.

based on the slight increase in the slope of the graph. The elastic modulus and strength of a composite can be predicted by using the rule of mixture equation;  $E_c = fE_f + (1 - f)E_m$ , based on the E modulus of the matrix ( $E_m$ ), E modulus of fibers ( $E_f$ ), and Volume fraction of fibers (f). Therefore, the addition of flax fiber, which has a higher elastic modulus, increased the samples' elastic modulus.

Before the failure, the deflection limit was similar among Portland Cement samples, which consistently withstand more significant displacement before collapse than the flax samples but only at less sustained forces.

As all samples have a uniform span, normalizing the equation changes the values over the x-axis consistently. The findings demonstrated that honeycomb with 19.05 mm thickness had a better flexural strength than the one with 10.16 mm as they can tolerate more loads. In addition, the addition of flax fibers is effective in prolonging early-stage cracking due to the tensile characteristics they add to the honeycomb sandwich panels.

Figure 4.3 shows the average ultimate strength of each sample type (based on the average loads applied to the samples and average dimensions of the specimens) and the standard deviation bars. Based on the findings, PC<sub>thin</sub> had the lowest average maximum strength of 0.87 MPa and the highest standard deviation of 0.40 MPa. The standard deviation of PC<sub>thick</sub> was also high at 0.31 MPa; however, the average ultimate strength was slightly higher at 1.02MPa. In the category of Portland cement samples, a large overlap in standard deviations of PC<sub>thin</sub> and PC<sub>thick</sub> presented that the increase in honeycomb thickness provides minimal improvements in strength reliability and has approximately the same average flexural strength. Contrarily, both Flax<sub>thin</sub> and Flax<sub>thick</sub> exhibited consistent, reliable results with standard deviations of 0.13 MPa and 0.14 MPa, respectively. The change in honeycomb thickness from 10.16 mm to 19.05 mm for the flax samples resulted in a considerable increase in average ultimate strength from 1.55 MPa to 2.11 MPa. It was verified that the principal factors in determining the sample's stiffness are the material's modulus of elasticity and the structure's geometry in terms of the planar moment of

inertia [35]. Therefore, thick samples in which layers are located further from the axis of motion resulted in higher stiffness. Thus, the sandwich panel could be more resistant due to the higher stiffness. In addition, as the maximal strength is dependent on the combination of sandwich thickness and the core thickness, the thicker core withstood more loads than the thinner one. Overall, it was determined that the samples with flax fibers exhibited less variability in results, and their flexural strength is superior to the PC panels. By using the average values, as  $Flax_{thin}$  performed 44% better than the  $PC_{thin}$  and  $Flax_{thick}$  achieved 52% better than the  $PC_{thick}$ , this study was mainly focused on analyzing the thermal performance, density, and water vapor transmission of flax fiber samples.

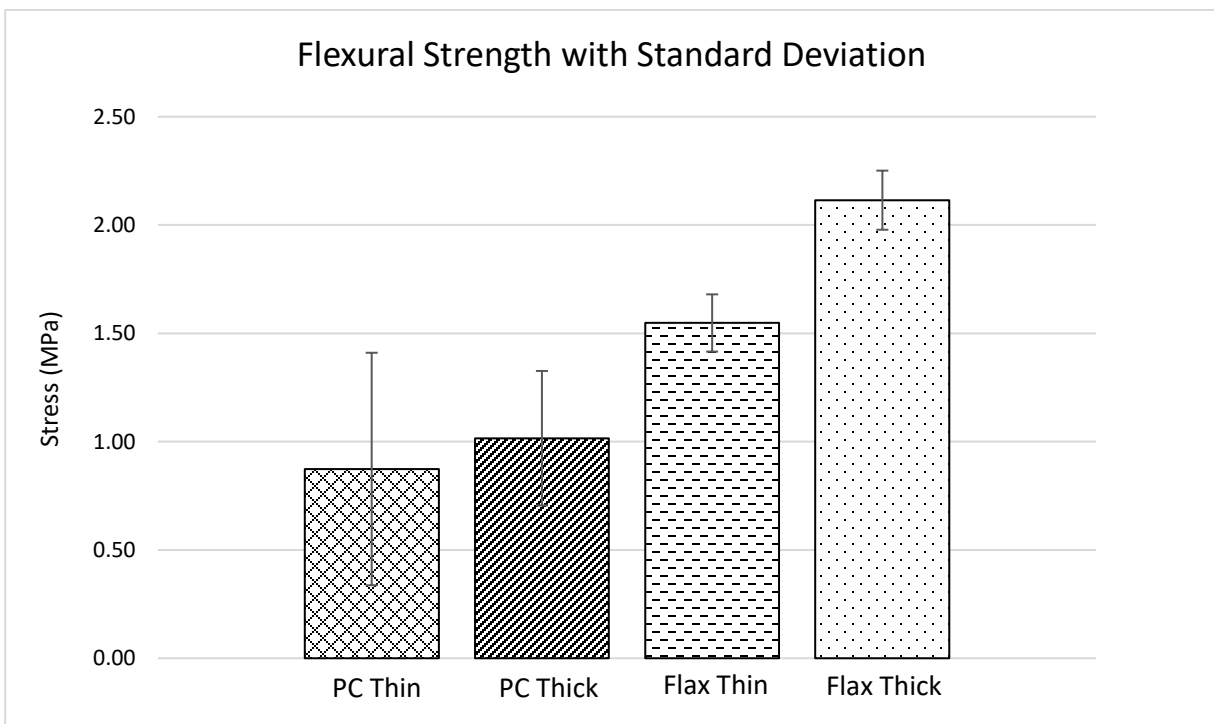


Figure 4.3. The average ultimate strength of honeycomb sandwich panels with standard deviation.

#### 4.4.2. Thermal Analysis

This section presents and discusses the thermal performance of two different thicknesses of honeycomb sandwich panels with the addition of flax fibers. Figure 4.4 shows the average thermal conductivities of the sandwich panels and the gypsum board. Overall, there is a significant difference between the thermal conductivity of gypsum board and sandwich samples. Findings indicated that the thermal conductivity of kraft-paper honeycomb sandwich panels was lower than

that of the gypsum board. The incorporation of kraft-paper honeycomb in the cementitious panels has an interrelated effect on decreasing the thermal conductivity of samples because of the lower thermal conductivity of kraft-paper honeycomb compared to gypsum board. Results presented that average thermal conductivities of gypsum board,  $Flax_{thin}$ , and  $Flax_{thick}$  were 0.159, 0.097, 0.092, W/m. K, respectively. The likely reason for the lower thermal conductivity of the thick sample is that by increasing the core thickness, the amount of air volume in the volume of honeycomb increases. Therefore, a decrease in the sample's thermal conductivity happened due to the low thermal conductivity of air compared to the thermal conductivity of the kraft-paper honeycomb sandwich panel. The thermal conductivity of the gypsum board ranges from 0.154 W/m. K to 0.164 W/m. K with an average of 0.159 W/m. K. However, the thermal conductivity of  $Flax_{thin}$ , and  $Flax_{thick}$  was reduced by 39% and 42%, respectively, compared to the gypsum board.

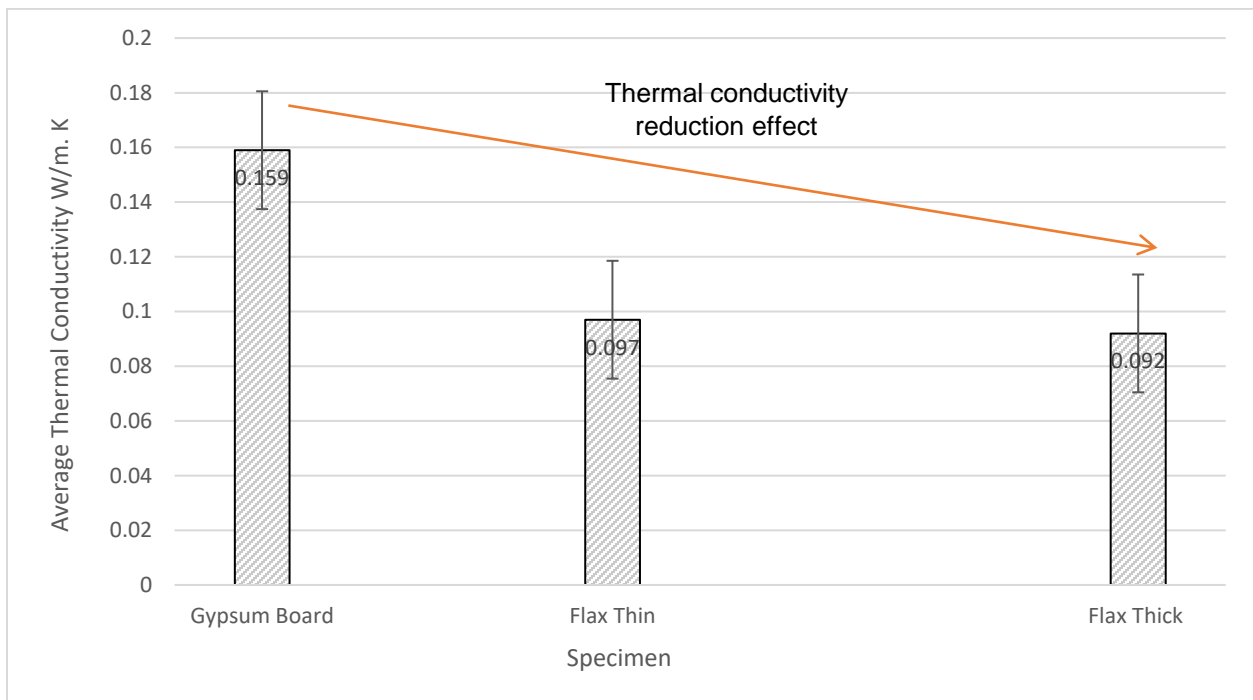


Figure 4.4. Average thermal conductivity of gypsum board,  $Flax_{thin}$ , and  $Flax_{thick}$ .

Figure 4.5 compares the mean value of the coefficient of thermal conductivity of two kraft-paper honeycomb sandwich panels measured as a function of temperature, ranging from -10 °C to 80 °C, against the thermal conductivity of gypsum board. The results illustrate that the thermal

conductivity of both samples increased almost linearly by increasing temperature. However, the coefficient of thermal conductivity of both  $\text{Flax}_{\text{thin}}$ , and  $\text{Flax}_{\text{thick}}$  were lower as compared to the gypsum board. In fact, the effect of the distribution of pores is decreased in flax fibers reinforced panels. Therefore, the rate of heat transfer in the specimens was reduced. In addition, as natural fibers contain microporosity, the panels that contain these fibers can effectively reduce the heat conductivity of the specimens. In a kraft-paper honeycomb sandwich panel, heat is transferred by conduction through the core and paper and convection in the air voids. It is noticeable that as the sample becomes thicker, a higher decrease in conduction occurs due to the inverse proportion of the rate of heat transfer to the thickness of the sample. Therefore, as depicted in figure 3-5,  $\text{Flax}_{\text{thick}}$  exhibited a lower coefficient of thermal conductivity when compared to its thin counterpart. In this respect, the thermal conductivity of the thick sample ranges from 0.080 to 0.107 W/m.K with an average value of 0.092 W/m.K. However, the thermal conductivity of the thin sample is approximately 5.4% higher, ranging from 0.084 to 0.117 W/m.K with an average of 0.097 W/m.K. Therefore, as  $\text{Flax}_{\text{thick}}$  has lower thermal conductivity in comparison to  $\text{Flax}_{\text{thin}}$  and gypsum board, it shows better thermal performance and can be considered as a good thermal insulator.

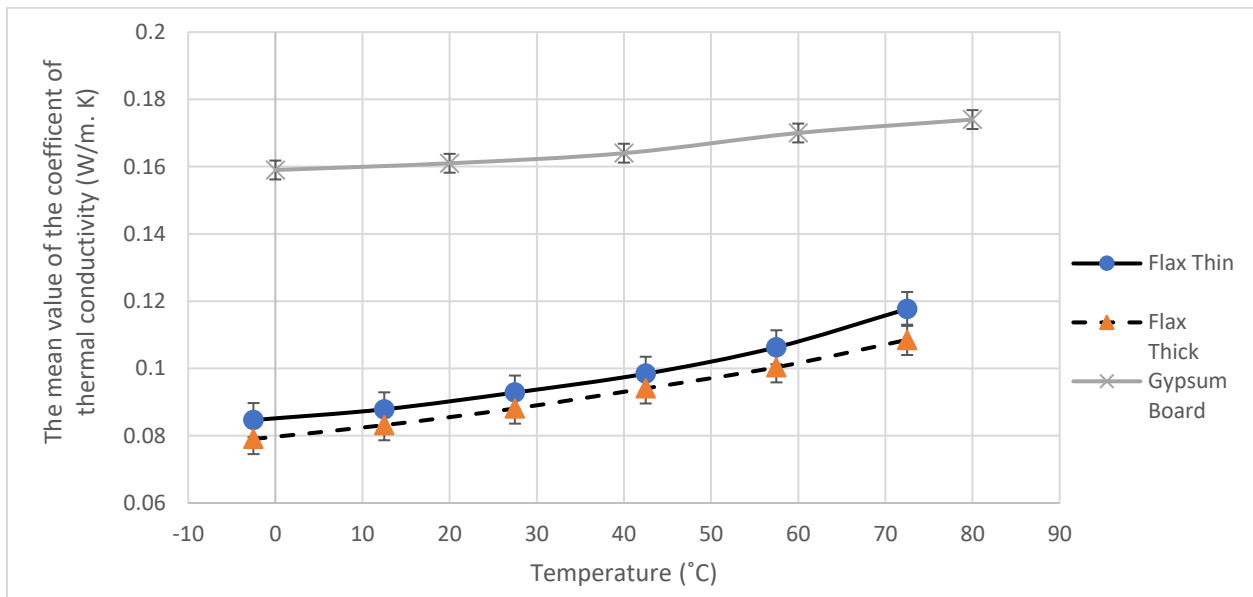


Figure 4.5. Thermal conductivity of kraft-paper honeycomb sandwich panels compared to gypsum board.

### 4.4.3. Density Measurement

Table 4.3 summarizes the kraft-paper honeycomb cementitious panels' volume, mass, standard deviation, and samples' densities. A low-density material is favorable because historically it can provide thermal insulation. As density is a measure of mass per volume, the average density of a specimen equals its total mass divided by its total volume. Figure 4.6 presents the samples within the density range from 0.60 g/cm<sup>3</sup> to 1 g/cm<sup>3</sup>. Possibilities for differences in the density of samples include different values of mass and volume due to the different honeycomb core thicknesses. In addition, samples with different thicknesses resulted in different densities because the relative density of honeycomb sandwich panels is proportional to the wall thickness to a wall-length ratio (t/L).

In the category of Portland Cement samples, PC<sub>thick</sub> has the lower average density and standard deviation in comparison to PC<sub>thin</sub>. On the other hand, the average density and standard deviation of Flax<sub>thick</sub> is lower compared to Flax<sub>thin</sub>. Therefore, the results revealed that the thick specimens of the study had the lowest densities with 0.76 g/cm<sup>3</sup> and 0.67 g/cm<sup>3</sup>. The likely reason for the decrease in Flax<sub>thick</sub> is the more significant amount of void volume than Flax<sub>thin</sub>. As the core layer of the kraft-paper honeycomb sandwich panel is a porous structure, in thick samples, the cross-sectional area of the solid part of the honeycomb panel is smaller than its volume void. Although Flax<sub>thin</sub> and Flax<sub>thick</sub> share the same cross-sectional composition, Flax<sub>thick</sub> has a larger height, making the void volume much more significant compared to Flax<sub>thin</sub>. Therefore, a thicker honeycomb core results in a lower density compared to the thinner specimens. In addition, the other explanation is related to the highest average volume of approximately 270,500 mm<sup>3</sup> and 251,400 mm<sup>3</sup> of Flax<sub>thick</sub> and PC<sub>thick</sub> which resulted in lower densities. However, PC<sub>thin</sub> and Flax<sub>thin</sub> with average volumes of 178,360 mm<sup>3</sup> and 250,000 mm<sup>3</sup> have the highest average densities of 0.99 g/cm<sup>3</sup> and 0.89 g/cm<sup>3</sup>, respectively.

Table 4.3. Honeycomb sandwich panel densities.

<b>Sample</b>	<b>Average Volume</b> (mm <sup>3</sup> )	<b>Average Mass</b> (g)	<b>Average Density</b> g/cm <sup>3</sup>	<b>Standard Deviation</b> g/cm <sup>3</sup>
<b>PC<sub>thin</sub></b>	178,360	175.38	0.99	0.086
<b>PC<sub>thick</sub></b>	251,400	243.77	0.76	0.069
<b>Flax<sub>thin</sub></b>	250,000	221.6	0.89	0.068
<b>Flax<sub>thick</sub></b>	270,500	183.6	0.67	0.051

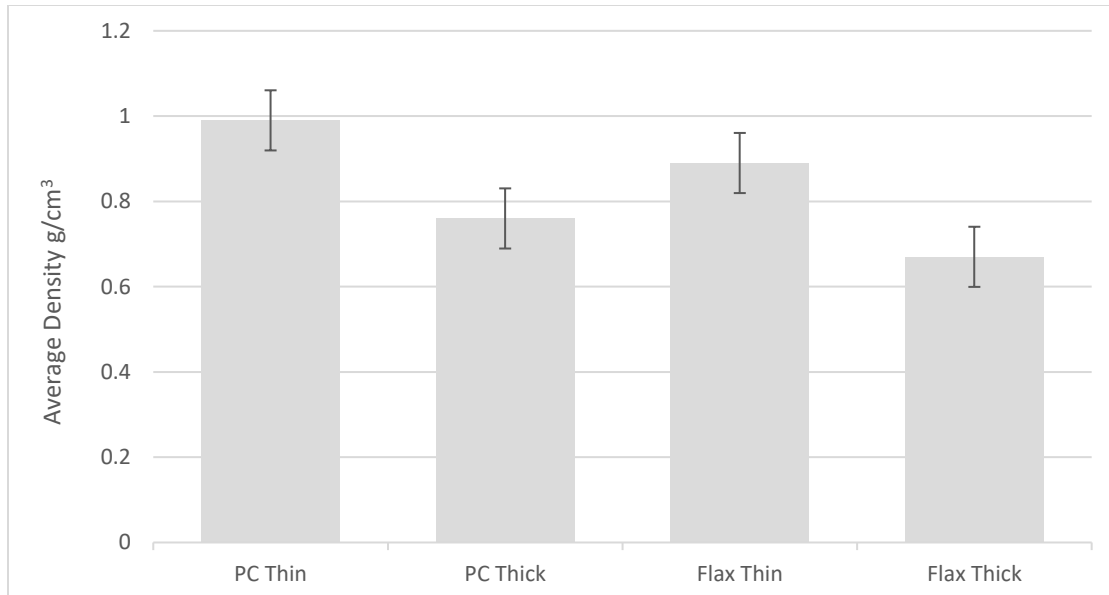


Figure 4.6. Average densities of honeycomb structures.

#### 4.4.4. Water Vapor Transmission

Water vapor transmission indicates the degree to which water vapor is transferred through a substance under a specific temperature and from regions of high relative humidity to regions of low relative humidity. Findings indicated a linear relationship between the total weight loss of dish assembly of water as a function of time. According to the ASTM standard, the slope of the line corresponding to the water vapor transmission rate. Figure 4.7 illustrates the average values of water vapor transmission of the flax-reinforced samples after reaching a steady-state at the time of 23 hours where the rate of weight change is substantially constant. The results showed that  $Flax_{thick}$  had a lower average water vapor transmission compared to  $Flax_{thin}$  with the amounts of  $17.93 \text{ g/h.m}^2$  and  $8.88 \text{ g/h.m}^2$ , respectively. It was confirmed that water vapor transfer through building components is mainly dependent on two mechanisms of air leakage and diffusion [36]. However, as kraft-paper honeycomb is a closed-cell structure, air leakage can be considered as less of a significant factor than diffusion. In addition, as water vapor transmission is affected by the thickness of the materials,  $Flax_{thick}$  exhibited a higher decrease in the rate of water vapor diffusion. Figure 4.8 compares the average water permeance of two kraft-paper honeycomb sandwich panels. As permeance is inversely proportional to the thickness and directly related to water vapor transmission rate,  $Flax_{thick}$  with a rise of core thickness resulted in lower permeance

rather than  $\text{Flax}_{\text{thin}}$ . The average permeance of  $\text{Flax}_{\text{thin}}$  and  $\text{Flax}_{\text{thick}}$  were 1.398 perms and 1.338 perms, respectively. Therefore,  $\text{Flax}_{\text{thick}}$  can be considered as an adequate water-resistant material.

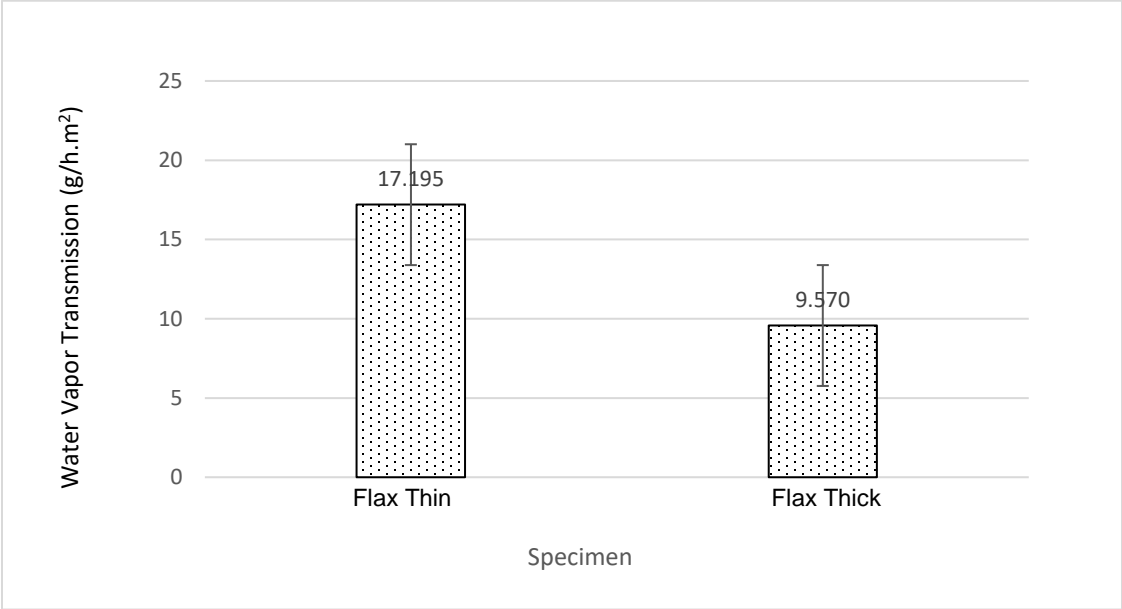


Figure 4.7. Average water vapor transmission of honeycomb structures.

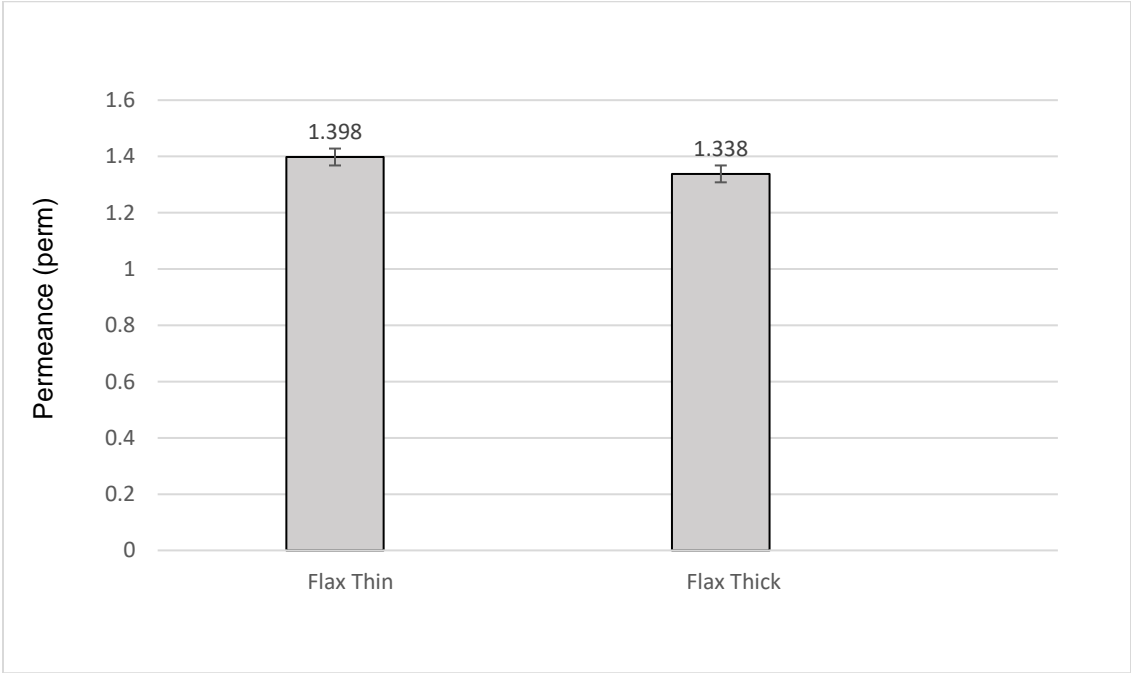


Figure 4.8. Average permeance of honeycomb structures.

## 4.5. Conclusion

This study developed kraft-paper honeycomb sandwich panels consisting of two different cementitious boards (Portland Cement and Portland Cement reinforced with flax fibers) to improve the mechanical and physical properties of drywall panels as an alternative to the gypsum-based boards in residential and commercial buildings. In addition, the results and findings of this report provide new and valuable design recommendations regarding material properties and the temperature range of new kraft-paper honeycomb sandwich panels. The main conclusions achieved in this investigation can be summarized as follows:

- The incorporation of flax fibers into the Portland Cement mixtures increases samples' stiffness and prolongs the early-stage cracking of non-flax fibers specimens. These significant enhancements are because of the unique properties of flax fibers in resisting greater bending and fracture forces than the brittle Portland Cement mixtures. Particularly, the 19.05 mm kraft paper honeycomb structure has approximately 41% higher flexural performance than the kraft-paper honeycomb sandwich panel with a thickness of 10.16 mm. As both sandwich thickness and core thickness factors influence the maximal strength, the sample with a thicker core tolerated higher loads than a thin sample. In addition, increasing the core thickness resulted in higher stiffness and resistance against bending and bucking loads due to the higher moment of inertia.
- Due to flax fibers' lower thermal conductivity and better thermal insulation properties, all flax fiber-reinforced panels exhibited lower thermal conductivity than the gypsum-based drywall. However, the thermal conductivity of  $\text{Flax}_{\text{thick}}$  showed a greater reduction of 42% compared to the gypsum board. The thermal analysis results confirmed that the samples' air volume increased by raising the thickness of the sample. Therefore,  $\text{Flax}_{\text{thick}}$  effectively decreased the coefficient of thermal conductivity compared to  $\text{Flax}_{\text{thin}}$  in different temperatures and is more resistant against a heat flow due to its higher embodied porosity. The results indicated that the thermal conductivity of  $\text{Flax}_{\text{thin}}$  as a function of temperature, ranging from  $-10\text{ }^{\circ}\text{C}$  to  $80\text{ }^{\circ}\text{C}$  is relatively 5.4% higher than the thermal conductivity of  $\text{Flax}_{\text{thick}}$ .
- Density measurements carried out on kraft-paper honeycomb sandwich panels showed a reduction in density by adding flax fibers to the cementitious boards. In addition, for equal

fiber content, the density of the sample with a thick honeycomb core is approximately 24% lower than that of  $Flax_{thin}$ . This remains possible due to the highest average volume and larger void volume in  $Flax_{thick}$  samples compared to the specimens with a thicker core.

- The water vapor transmission and permeance analysis indicated that  $Flax_{thick}$  samples with a core thickness of 19.05 mm had lower values with the amounts of 8.88 g/h.m<sup>2</sup> and 1.291 perms, respectively in comparison to  $Flax_{thin}$  sample. In effect, as kraft-paper honeycomb is a closed-cell structure, the diffusion mechanism mainly affects the rate of water vapor transmission. Therefore, samples with thick cores exhibited more decrease in the amount of water vapor diffusion and permeance.

Therefore, this study highlighted that the impregnation of flax fibers in a multilayer sandwich structure with a thicker core resulted in higher flexural strength, superior thermal performance, lower density, and lesser water vapor transmission rate. Therefore, flax-fiber reinforced kraft-paper honeycomb cementitious sandwich panels can be considered as a functional material for improving the physical and mechanical properties of drywall while providing a substantial increase in R-value when compared to  $Flax_{thin}$  and gypsum-board. Furthermore, drywall is highly susceptible to microbial growth due to the cellulosic paper backing. This microorganism can affect the thermal comfort and air quality of a dwelling unit over time. Therefore, since the environmental impacts of mold and mildew growth are essential factors in material selection, further research is needed to evaluate the hygrothermal performance and environmental interactions of the proposed kraft-paper honeycomb sandwich panel. In this regard, subsequent work should include the use of collected experimental data as an input to a numerical computer simulation to validate the developed model due to the lack of comparison of numerical simulation results and the experimental measurements.

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## CHAPTER 5

### **5. Hygrothermal Performance of a New Composite Sandwich Panel Alternative to Gypsum Drywall Using a Heat and Moisture Modelling**

#### **5.1. Abstract**

Gypsum-base drywall as a wall or ceiling finishing material is to protect wall assemblies from environmental impacts. However, the gypsum drywall is prone to water and moisture problems such as condensation risk and mold growth due to its low water resistance. The study aims to introduce an alternative- a sandwich panel composed of two cementitious layers bonded to a low-density kraft paper honeycomb core to the gypsum drywall- and to investigate its hygrothermal performance. Therefore, two different wall structures of a conventional wall assembly with gypsum-based drywall and a developed sandwich panel were designed in WUFI Pro under boundary conditions of a cold year in the Ottawa region with medium and high moisture loads over five years. The water content, relative humidity, condensation risk and mold growth, and thermal performance were determined. The findings indicate that the proposed sandwich panel has significantly lower water content and better thermal performance of roughly 4.6% comparing to the gypsum-based drywall.

#### **5.2. Introduction**

The choice of building materials can significantly impact the sustainability of construction projects. Therefore, research and technological development try to improve building materials' performance and environmental sustainability. However, certain materials such as gypsum-derived materials have remained unchanged. For example, gypsum and gypsum-derived materials such as drywall have been extensively used as construction materials since the early 1900s due to the excellent availability of primary ingredients [1,2]. The gypsum-based drywall is the most

common indoor building material of walls and ceilings with either Light Steel Framing or Light Timber Framing [3].

Although gypsum boards have advantages such as ease of workability, low cost, and fire resistance they have disadvantages such as relatively high thermal conductivity, high moisture permeability, and low water resistance [4]. Consequently, the drywall does not offer any notable insulating improvements and may adversely affect the physical properties of a wall assembly[4]. In addition, the indoor air quality of a house can be affected because the drywall can be easily compromised by mold and mildew growth in humid climates and in the event of a leak or flood. Moreover, because gypsum-based drywall disposal in the deconstruction of civil structures lacks proper support from recycling facilities, it is more common to dispose of drywall waste in landfills. The moist, anaerobic conditions of the landfill can affect anaerobic microorganisms (sulfate-reducing bacteria) in drywall components [5]. Therefore, drywall decomposition can contaminate both surface and groundwater by increasing the sulfate content in the landfill leachate [6].

Considering thermal comfort and indoor air quality are vital factors in designing energy-efficient buildings [7]. Indoor humidity, which affects perceived indoor air quality, is principal to the comfort and durability of construction materials [8]. The durability of building material is its ability to keep its efficiency for a long time without remarkable deterioration and requiring minimum maintenance. Indoor moisture can originate from various sources, including 1) indoor activities such as cooking, showering, and cleaning [9], 2) groundwater intrusion and penetration of precipitation [10], 3) building design and operational issues such as plumbing leaks and uncontrolled airflows [11]. Because these occurrences in buildings can cause many problems, such as structural damage, mold growth, decay of the building materials, and health concerns, moisture control has become a worldwide issue due to the changes in building operations and construction practices [13,14,15]. Therefore, functional building materials with improvements in hygrothermal properties are key to providing the dwellers with healthy indoor air quality and thermal comfort.

In the research conducted by Seong Jin Chang and Sumin Kim (2015), the transient hygrothermal modeling tool WUFI Pro 5.3 was used to examine two different wood and concrete wall structures [15]. The findings indicated that for the long-term moisture performance, the total water content of the concrete wall with an average value of  $13.8 \text{ kg/m}^3$  was significantly higher than the entire water content of the wood frame wall with a layer of gypsum board with an average of  $2.85 \text{ kg/m}^3$

[15]. In addition, both wall assemblies have condensation risk in the winter season with low-temperature levels. However, the wood-frame structure with gypsum board showed a higher mold growth risk at a relative humidity of approximately 78% than the concrete structure [15]. Moreover, Seong Jin Chang and Sumin Kim (2018) evaluated the hygrothermal behavior of concrete walls with a layer of gypsum board added with porous materials. The results showed that adding porous materials such as carbon nanomaterials to the gypsum board effectively improves the thermal and hygroscopic performance of the insulation close to the gypsum board with lower water content [16]. However, porous materials such as expanded vermiculite and expanded perlite, which are less hygroscopic, could negatively influence the thermal performance of the insulation [16].

Sandwich structures are gaining popularity as structural building components in the construction industry due to their high performance, high stiffness-to-weight ratio, energy efficiency, higher thermal and acoustic properties, and reduction in the cost of the framework [17,18,19]. Due to these advantages, sandwich structures are actively considered in different engineering applications, including marine, automotive, and sports equipment [20,21]. In addition, sandwich panels have been commonly used in commercial and residential building systems because of their ability to enhance thermal and structural performance [22]. Sandwich panels consist of a core layer with a low-density material bonded with two thin, stiff, and strong face sheets with a dense material. Faces are commonly made of non-cementitious materials such as ceramics, aluminum, and wood. Rigid foams such as polyurethane, polyisocyanurate, and polystyrene can be considered as core materials due to their low thermal conductivity and high moisture resistance [20]. However, as foam plastics are a fire hazard material, the kraft-paper honeycomb was regarded as a core to increase the fire performance of the sandwich panel [21].

In our previous study, we developed a proposed solution to the pitfalls of gypsum-based drywall, a cementitious kraft paper honeycomb panel with better mechanical and physical performance [23]. The honeycomb sandwich panel comprises an internal core layer made of a low-density honeycomb bonded with high-density external face sheets [19,24]. In this study, the cementitious boards with flax fibers were considered outer faces due to their superior mechanical properties, high fire resistance, and low environmental impacts. The results indicated that impregnation of flax fibers to the mixture presented an increase in the samples' flexural strength due to the unique

properties of flax fibers in tolerating more load than the brittle Portland cement [23]. Moreover, flax fiber-reinforced kraft paper honeycomb panels showed a lower water vapor transmission rate and a more significant reduction of 42% of thermal conductivity than the gypsum-based drywall due to the better thermal insulation properties of flax fibers [23]. Although flax-fiber reinforced kraft-paper honeycomb cementitious sandwich panels presented better physical and mechanical properties than the gypsum-based drywall, the long-term hygrothermal behavior of the proposed sandwich panel should be evaluated.

Predicting hygrothermal performance is necessary to improve the assembly's performance and durability in its service life [25]. In the last 20 years, different numerical modeling tools have been developed to study the long-term hygrothermal behavior of building envelope components exposed to diverse climatic conditions in various geographical locations [26]. Low cost and time-saving could be considered the advantages of validated numerical modeling compared to the experimental methods [25]. In addition, modeling leads to a more precise understanding of hygrothermal performance and more detailed predictions of overall performance in buildings [15]. Furthermore, theoretical analysis coupled with laboratory experiments can enable verification of the accuracy of hygrothermal models based on a series of presumptions [25].

This research thesis aims to evaluate the hygrothermal performance of a wall assembly that involves a kraft-paper honeycomb cementitious sandwich panel compared with conventional gypsum-based drywall in the Canadian climate context. One-dimensional (1D) moisture performance simulation model WUFI Pro 6.5 software was selected for this study. WUFI is a program for determining the hygrothermal analysis of the building components under actual climatic conditions, considering wind-driven rain, build-in moisture, solar radiation, capillary transport [15]. Consequently, a numerical simulation analysis brings an opportunity to extend the experimental results found in the previous study. In addition, the numerical analysis was performed for both of the wall assemblies for five consecutive years, ranging from 1<sup>st</sup> January 2016 to 31<sup>st</sup> December 2020. The output provides valuable information about the water content in individual layers, relative humidity, heat flow, and the monitor position isopleths.

## **5.3. Simulation Parameters**

### **5.3.1. Wall Assembly Configurations**

The National Energy Code of Canada for Buildings (NECB) which specifies energy-efficiency provisions for buildings, provides information regarding the minimum effective R-value requirements for different climate zones in Canada [27]. Based on NECB code requirements, Ottawa belongs to zone 6 (4000 to 4999 HDD), where the minimum R-value requirement for building enclosure assemblies is  $3.08 \text{ m}^2\text{k/W}$  for the above-grade wall assemblies [28]. This study followed these recommendations to define two types of wood-frame wall assemblies, including 1) reference wall and 2) multilayer sandwich panel. The reference case is determined based on Canada's literature review and conventional wall assembly. The multilayer sandwich panel is created based on the following standard practices outlined in ASTM C305 to construct cement panels and experiment with admixtures to improve material performance. Figure 5.1 presents the composition of the designed assemblies in WUFI Pro.

The reference wall is composed of regular lime stucco for the exterior finish, air layer for ventilation, extruded polystyrene insulation, oriented strand board (OSB), fiberglass, vapor retarder, and interior gypsum board complies with the recommended minimum code requirements.

The multilayer sandwich panel is composed of regular lime stucco for the exterior finish, air layer for ventilation, extruded polystyrene insulation, oriented strand board (OSB), fiberglass, vapor retarder, and kraft-paper honeycomb sandwich panel.

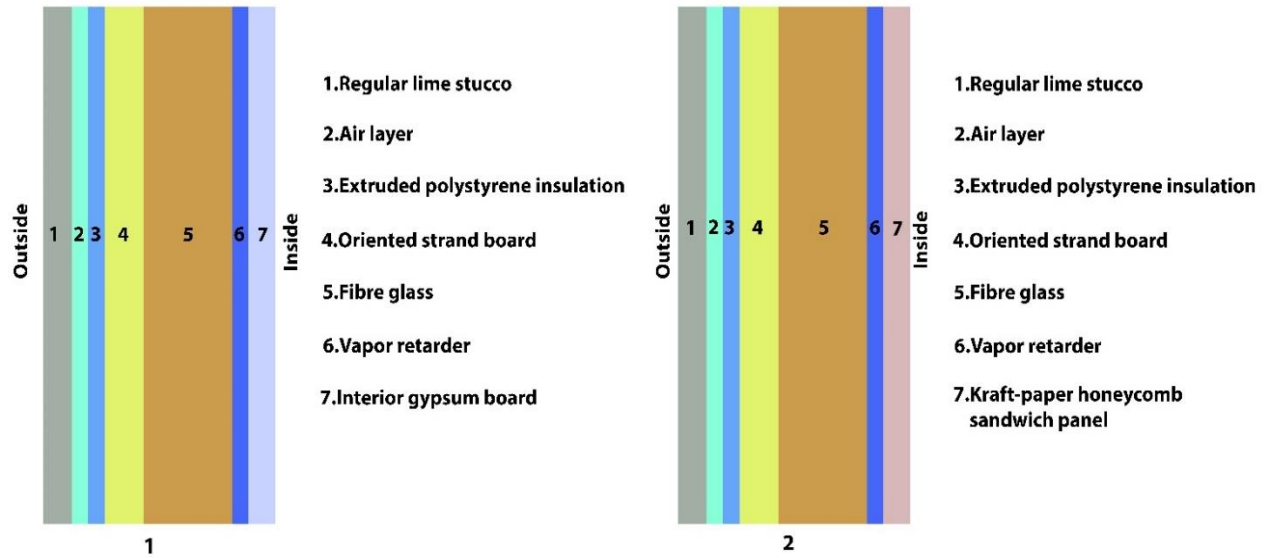


Figure 5.1. The composition of 1) reference wall 2) multilayer sandwich panel for numerical modeling.

The physical properties of all materials used in simulations were derived from experimental data and the WUFI database [29]. Regular lime stucco was selected from a section of the North American database. An air layer with a thickness of 25 mm was considered from the air layer section of generic materials. The two insulations of extruded polystyrene insulation and fiberglass and one insulation of vapor retarder were available in the insulation materials and membranes section of the North American database. OSB and interior gypsum boards' properties could be found in the North American database's building boards and sidings section. As Kraft-paper honeycomb sandwich panel's properties were not included in the WUFI library, experimental data was selected to define thermal conductivity, porosity, bulk density, specific heat capacity, and water vapor diffusion resistance factor of flax-fiber reinforced kraft paper honeycomb cementitious sandwich panels. Based on the information selected in WUFI software, it was calculated that the reference case with an R-value of 5.41 m<sup>2</sup>K/W and multilayer sandwich panel with an R-value of 5.66 met the minimum defined code requirements for building enclosure assemblies in Ottawa. Table 5.1 summarizes the basic material properties assumed for drywall assembly and kraft paper honeycomb sandwich panel.

Table 5.1. Material properties of drywall assembly used in numerical analysis.

Property	Thickness [m]	Bulk Density [kg/m <sup>3</sup> ]	Porosity [m <sup>3</sup> /m <sup>3</sup> ]	Spec. Heat Capacity (J/kg K)	Thermal Conductivity (W/mK)	Water Vapor Diffusion Resistance Factor (-)
Regular Lime Stucco	0.019	1769	0.274	840	0.343	310.6
Air Layer	0.025	1.3	0.999	1000	0.155	0.51
Extruded Polystyrene Insulation	0.0254	28.6	0.99	1470	0.025	170.56
Oriented Strand Board	0.0125	650	0.95	1880	0.092	812.8
Fiber Glass	0.14	30	0.99	840	0.035	1.3
Vapor Retarder (1 perm)	0.001	130	0.001	2300	2.3	3280
Interior Gypsum Board	0.0125	625	0.706	870	0.16	7.03
Kraft-paper honeycomb sandwich panel	0.3155	670	0.55	1090	0.092	3.59

### 5.3.2. Boundary Conditions

The initial conditions of the materials should be defined in WUFI Pro software to redirect the content into its starting value and observe the flow cycle throughout the year [30]. Table 5.2 illustrates the initial conditions applied to the materials of the assemblies based on the WUFI library and literature [29].

Table 5.2. initial properties of materials

Material	Temperature °C	Water Content [kg/m <sup>3</sup> ]	Relative Humidity %
Regular Lime Stucco	20	120.3	80
Air Layer		2.88	
Extruded Polystyrene Insulation		0.31	
Oriented Strand Board		83.25	
Fiber Glass		1.86	
Vapor Retarder		0	
Interior Gypsum Board		8.65	
Kraft-paper honeycomb sandwich panel		1.8	

In this study, the orientation of the South-East, which is the compass direction towards which the building component is facing, was considered to maximize the combination of sun exposure. Both wall assemblies were set with 90° inclination and a short height of 10 m for driving rain coefficients. In terms of surface transfer coefficients, default values were selected for the heat resistance of both exterior and interior surfaces. The heat resistance of the exterior surface (left side) was 0.0588 (m<sup>2</sup>K)/W without wind dependency. The internal surface heat resistance (right side) was 0.125 (m<sup>2</sup>K)/W. The short-wave radiation absorptivity of the exterior surface used for solar heating from the visible light spectrum was 0.4, corresponding to the stucco, standard bright setting [31]. No surface coating was considered for both sides of the wall enclosures regarding the sd values. The sd-value of a layer describes the diffusion resistance of the layer in terms of thickness (in meters). Therefore, for the building components without any coating surface, the sd-value is equal to zero (sd=0 m). The calculation period of five years (from 1-1-2016 to 31-12-2020) was selected for evaluating the long-term hygrothermal performance of wall assemblies.

### **5.3.3. Climate file**

Surface boundary conditions should be defined in WUFI software to analyze the model for specific indoor and outdoor climates. Boundary conditions in one-dimensional WUFI are included exterior climate (rain, sun, wind, relative humidity, temperature), interior weather conditions (temperature, relative humidity), and initial moisture contents. Several external and internal climatic boundary conditions that are different based on the location and severity are provided in the WUFI weather database. In this regard, two scenarios that combine one external and two internal boundary conditions were applied to both wall assemblies. The default WUFI climate file of the cold year within the Ottawa region was selected as an exterior climate for simulation. EN 15026, which is possible to include both medium and high moisture load in residential buildings, was used to define the interior climate. The medium moisture load is related to the residential and office spaces with normal occupancy. However, high moisture load defines the residential houses with high occupancy. In addition, the variation of the indoor air temperature is derived from the outdoor air temperature using a transfer function in this standard. For example, when outdoor temperatures are below 10°C, heating or air conditioning will keep the indoor temperature at 20°C; when outdoor temperatures are higher, the indoor temperature will rise linearly but not exceed 25°C.

Because heat and moisture are transferred across the symmetry axis in symmetric components, the top and bottom surfaces of the designed wall enclosures behave as an adiabatic or impermeable boundary. Table 5.3 illustrates the selected external and internal climatic conditions.

Table 5.3. Indoor and outdoor environmental boundary conditions.

Scenarios	Outdoor conditions	Indoor Conditions	
Scenario I	<b>Cold year</b> Maximum Temp= 36.1 °C Minimum Temp= -28.3 °C Mean Temp= 5.2 °C	<b>Medium moisture load</b> Maximum Temperature= 25 °C    Maximum RH= 60 % Minimum Temperature= 20 °C    Minimum RH= 30 % Mean Temperature= 22.5 °C    Mean RH= 45 %	
		<b>High moisture load</b> Maximum Temperature= 25 °C    Maximum RH= 70 % Minimum Temperature= 20 °C    Minimum RH= 40 % Mean Temperature= 22.5 °C    Mean RH= 55 %	
Scenario II	Maximum RH= 100 % Minimum RH= 18 % Mean RH= 67.4 %		

## 5.4. Hygrothermal Simulation Results

### 5.4.1. Moisture content

The water content of individual layers is considered a significant indicator in determining the condensation risk in the wall assemblies [32]. Figures 5.2 and 5.3 present the average monthly water content values ( $\text{kg/m}^3$ ) of individual layers of the reference wall and multilayer sandwich panel under two scenarios over five years of the analysis. Overall, the water content of all layers except the air layer initially decreased, then established a regular pattern of seasonal fluctuation. Results showed that although the amount of water content in fiber glass, gypsum board, and kraft paper was higher during the rainy days, both walls had maximum water content under scenario I and scenario II in July and the lowest water content in January indicating that it takes six months for walls to dry. In addition, air layer, fiber glass, gypsum board, and kraft paper honeycomb had a higher water content of approximately 6.5%, 32%, 18.5%, and 31.5%, respectively under scenario II compared to scenario I. Therefore, these layers performed better under scenario I with lower water content at the end of the simulation period. Moreover, the monthly average total water content of the air layer ranged from  $1.81 \text{ kg/m}^3$  to  $1.2 \text{ kg/m}^3$  with an average of  $1.14 \text{ kg/m}^3$  under scenario I and from  $1.82 \text{ kg/m}^3$  to  $1.3 \text{ kg/m}^3$  with an average of  $1.22 \text{ kg/m}^3$  under scenario II. The

monthly average total water content of fiber glass varied between  $0.89 \text{ kg/m}^3$  and  $0.42 \text{ kg/m}^3$  with an average amount of  $0.74 \text{ kg/m}^3$  under scenario I and between  $0.93 \text{ kg/m}^3$  and  $0.64 \text{ kg/m}^3$  with an average of  $1.09 \text{ kg/m}^3$  under scenario II. In addition, the results showed that the water content of the interior surface of kraft paper with an average of  $0.65 \text{ kg/m}^3$  under scenario I and  $0.95 \text{ kg/m}^3$  under scenario II were significantly lower than gypsum board with an average water content of  $4.02 \text{ kg/m}^3$  under scenario I and  $4.91 \text{ kg/m}^3$  under scenario II, respectively during the simulation period. Overall, it was concluded that the multilayer sandwich panel showed a more significant reduction of water content (approximately 83%) compared to the gypsum-based drywall assembly.

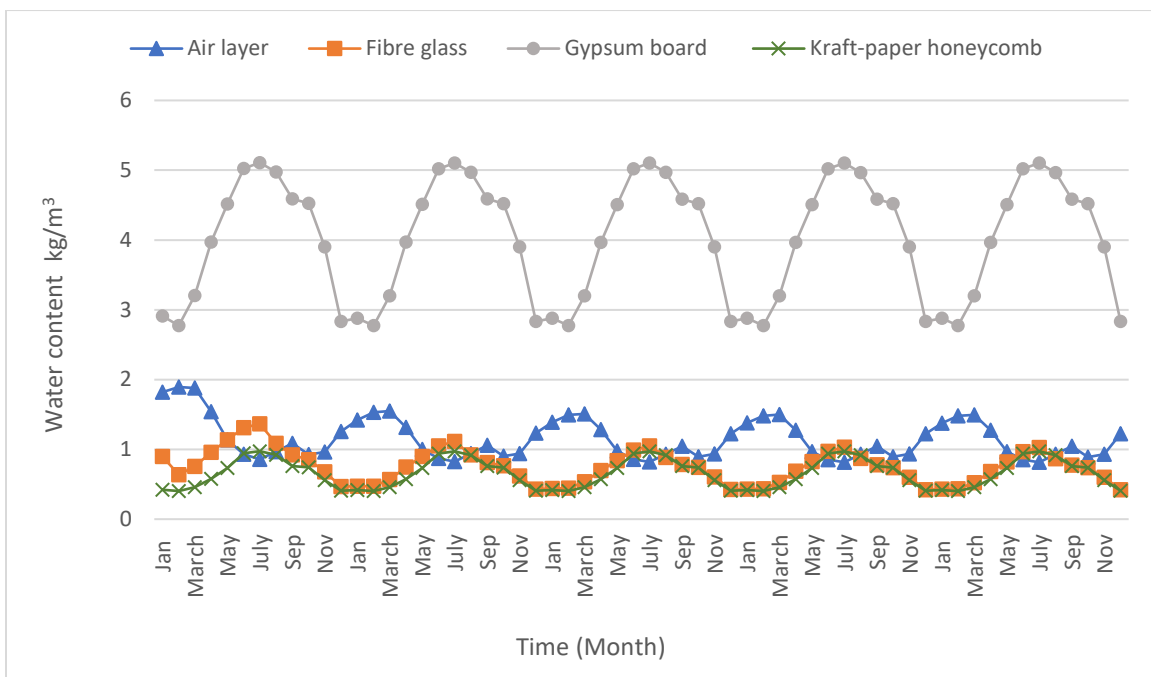


Figure 5.2. Average monthly total water content distributions of individual layers under scenario I.

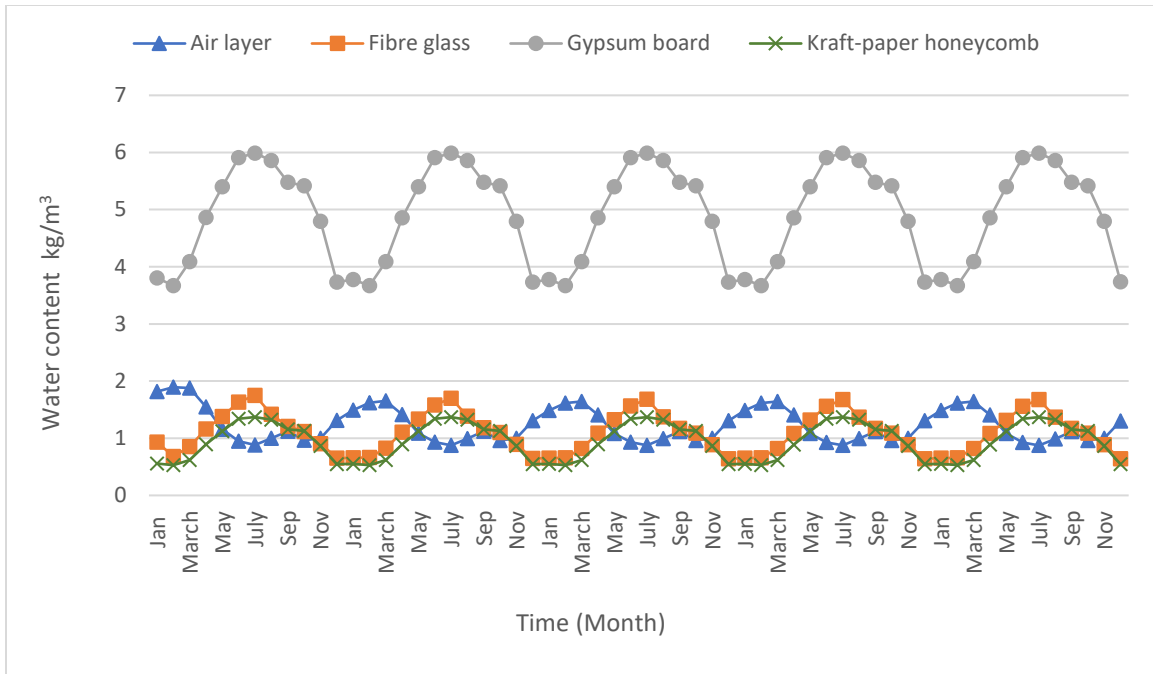


Figure 5.3. Average monthly total water content distributions of individual layers under scenario II.

Table 5.4 summarizes the average water content in mass percent of the reference wall and multilayer sandwich panel at the beginning and end of the calculation period. The findings indicated that the obtained values of both walls were significantly lower than the practiced standard of 20 mass percent of EN 15026/ DIN 4108 in WUFI. Therefore, no moisture accumulation would occur in the wall assemblies under both scenarios. In addition, it is evident that the total average water content of the reference wall and multilayer sandwich panel gradually decreased under both scenarios, demonstrating that the building envelopes were drying out during the simulation period.

Table 5.4. Average water content in mass percent of the reference wall and multilayer sandwich panel.

Scenario	Reference wall		Multilayer sandwich panel	
	2016	2020	2016	2020
	M%-Total	M%-Total	M%-Total	M%-Total
<b>I</b>	0.662	0.644	0.101	0.098
<b>II</b>	0.805	0.788	0.148	0.142

### 5.4.2. Relative humidity

Figures 5.4 and 5.5 present the relative humidity of different layers of the reference case and multilayer sandwich panel from 1<sup>st</sup> January 2020 to 31<sup>st</sup> December 2020 under the condition of medium moisture load, respectively at monitor positions distance from the outside: 0.004 m of Air layer, 0.0034 m of oriented strand board, 0.068 m of fiberglass, and 0.235 m of the interior surface of gypsum board and kraft paper honeycomb sandwich panel. Overall, the results indicate that individual layers of both wall assemblies had similar relative humidities over the last year of the calculation. In addition, the Monitor position of 0.0034 m where the oriented strand board is located in both walls showed high relative humidity in the winter and approximately low relative humidity in the summer. Furthermore, although the monitor location of the air layer presented high relative humidity at the start of the calculation, the relative humidity decreased during the summer. Monitor position of the interior surface of both the reference wall and the multilayer sandwich panel with kraft-paper honeycomb illustrated almost similar behavior with a slight difference during the calculation. Generally, according to WUFI annual and the EN 15026, a condensation risk might appear when the relative humidity of the biodegradable construction material is higher than 80% [33]. Therefore, As the relative humidity of the individual layers of both wall assemblies is below 80%, no condensation risk occurred during the calculation period.

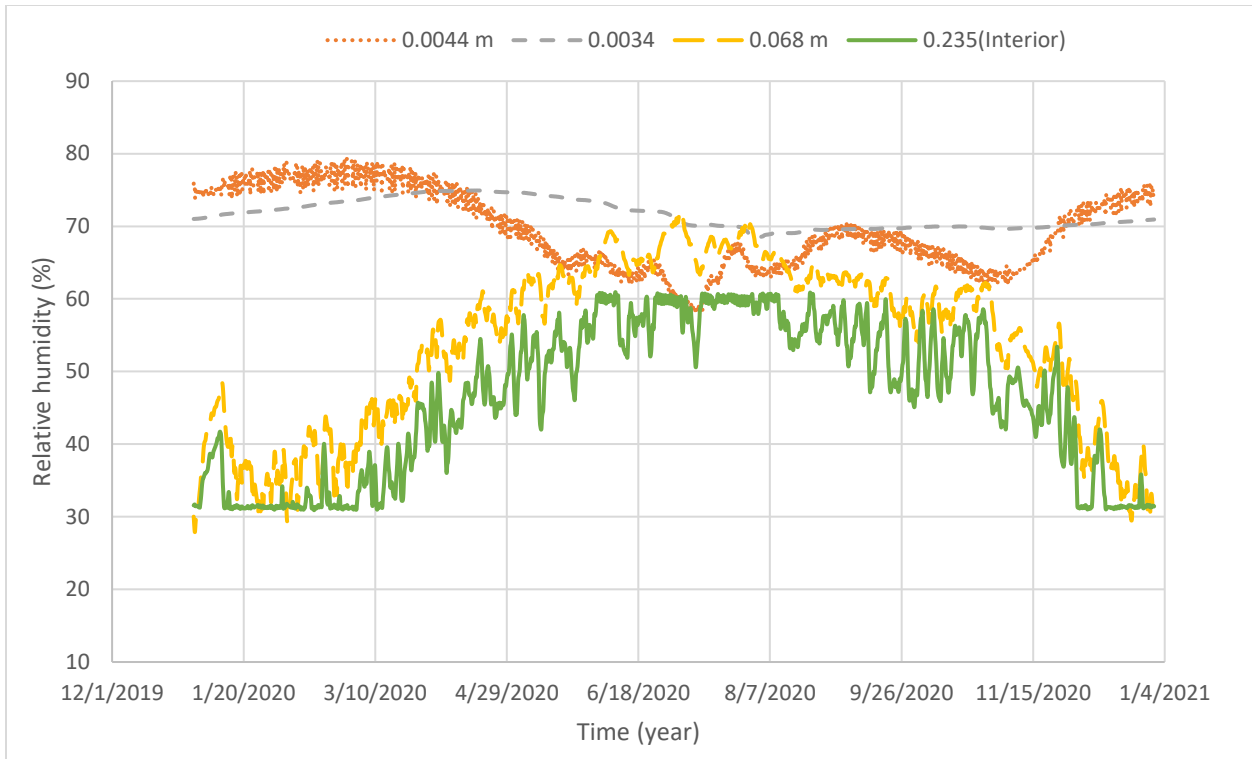


Figure 5.4. Relative humidity of different building layers of reference case under the scenario I.

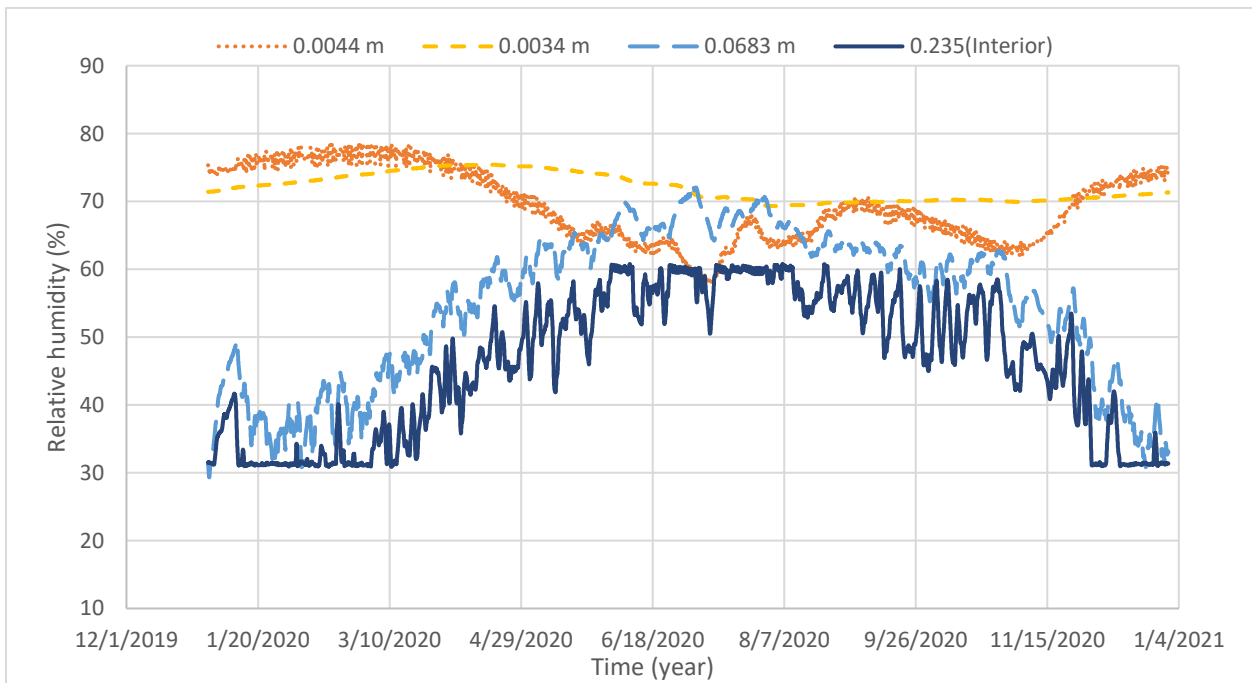


Figure 5.5. Relative humidity of different building layers of multilayer sandwich panel under the scenario I.

### 5.4.3. Condensation and mold risks of reference wall and multilayer sandwich panel

Figure 5.6 presents the average mold isopleths of the interior surface of both the reference wall and multilayer sandwich panel under two scenarios at three temperatures of 19 °C, 21 °C, and 25 °C. The findings indicate that no mold growth is observed as the relative humidity at the interior surface of gypsum board drywall and kraft-paper honeycomb sandwich panel assemblies lay below the relative humidity of 80% limiting isopleths. Furthermore, although the obtained relative humidity values were relatively similar under the same conditions for both wall assemblies, the reference wall and multilayer sandwich panel showed higher relative humidity under scenario II compared to scenario I. For example, under scenario I, the isopleths of the two wall assemblies occurred between relative humidity of 30% and 60%, with an average relative humidity of 38.9 %, 53.9%, 59.62% at a temperature of 19 °C, 21°C, and 25 °C, respectively. However, under scenario II, the isopleths of two wall assemblies are between relative humidity of 40% and 70%, with an average relative humidity of 49.21%, 64%, and 69.5% at temperatures of 19 °C, 21°C, and 25 °C, respectively. Overall, it can be concluded that under scenario I, the reference wall and multilayer sandwich panel perform approximately 20% at a temperature of 19 °C, 15% at a temperature of 21°C, and 14% at a temperature of 25 °C better than both wall assemblies under scenario II.

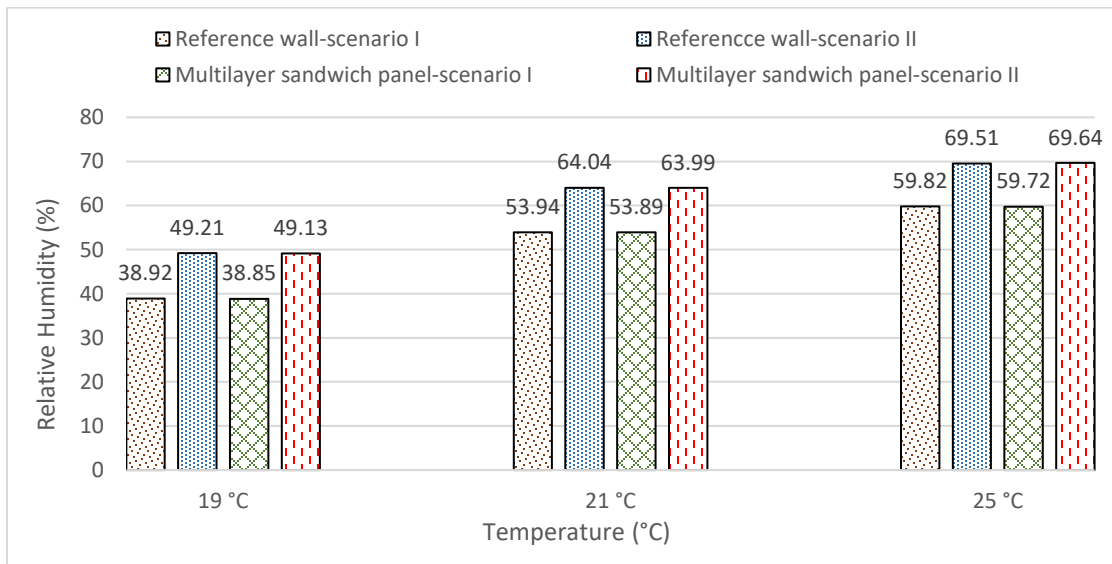


Figure 5.6. Average mold isopleths of the interior surface of both reference wall and multilayer sandwich panel under two scenarios.

### 5.4.3.1. Condensation and mold risks of individual gypsum board and kraft-paper honeycomb sandwich panel

The mold isopleth graph plots the surface temperatures of each time step against the corresponding relative humidities. Two curves in the graph present the limiting isopleths for building material, LIM B I and LIM B II. LIM B I is related to the bio-utilizable substrates, such as wallpaper, plasterboard; However, LIM B II represents substrates with porous structures, such as plasters, mineral building materials, and insulating materials [34]. Moreover, the color of each point indicated the time when the point occurred at the time of the calculation. The yellow color is related to points generated at the beginning of the analysis. Later, the yellow spots gradually turn into darker shades of green, and the last points of the calculation are defined in black color. This procedure provides an opportunity to identify any long-term trend in the cloud of spots [34].

Figures 5.7 and 5.8 illustrate the mold isopleths of the interior surface of the gypsum board and kraft paper honeycomb sandwich panel under the scenario I, with a medium moisture load. The results showed that as the scattered graph of relative humidity and temperature at the interior surface of the gypsum board lies above the limiting isopleths, mold growth is expected. However, as the isopleth of the kraft-paper honeycomb sandwich panel is below both limiting lines, no mold growth occurred and showed a better performance than the gypsum-based drywall.

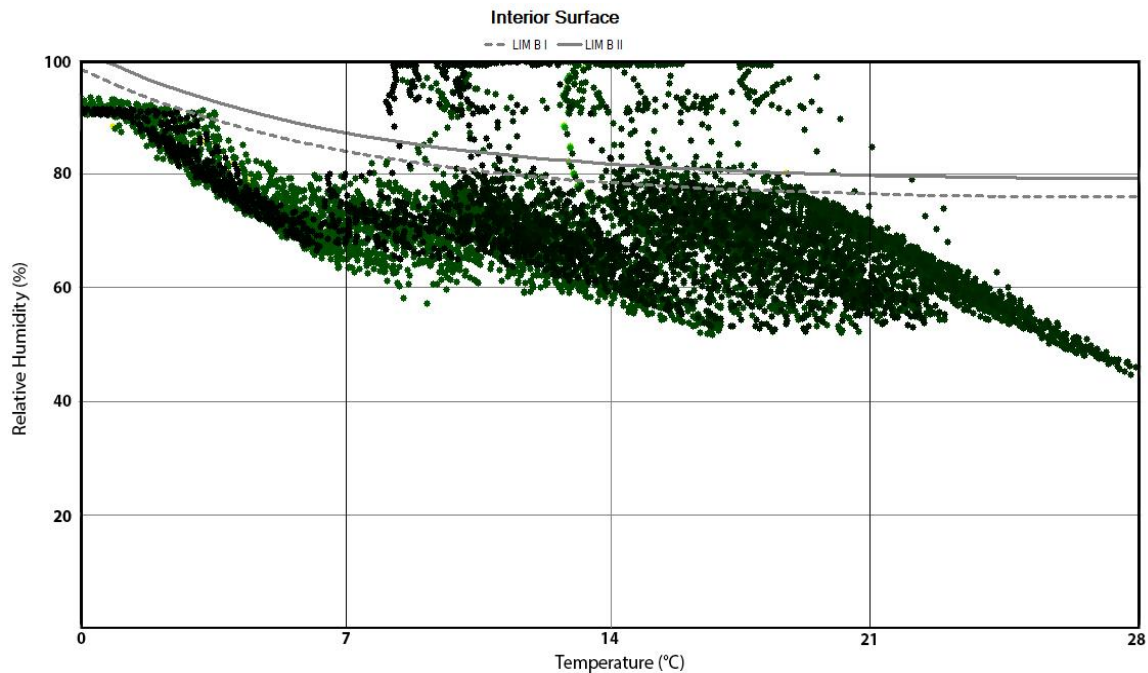


Figure 5.7. Mold isopleths at the Internal surface of the reference wall under scenario I.

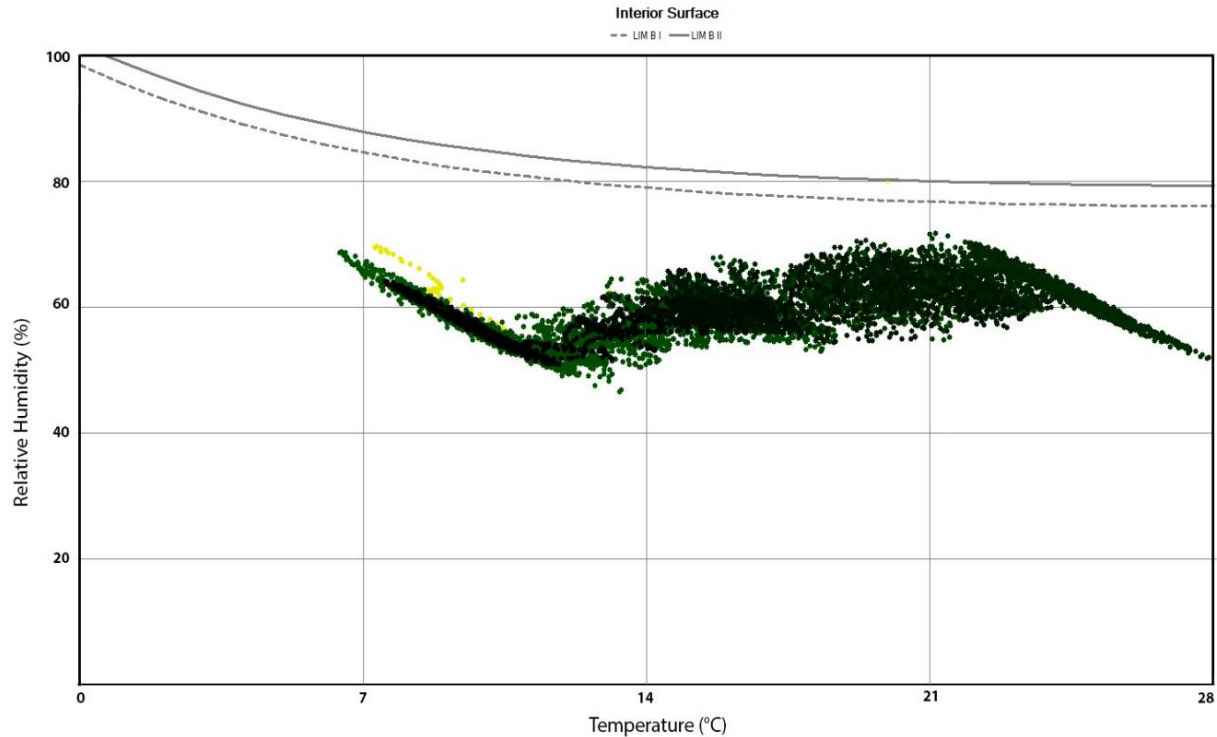


Figure 5.8. Mold isopleths at the Internal surface of the multilayer sandwich panel under scenario I.

#### 5.4.4. Thermal performance of the reference wall and multilayer sandwich panel

Figures 5.9 and 5.10 compare the total annual heat flows at both interior and exterior surfaces of both wall assemblies under two scenarios of I and II over five consecutive years, respectively. Overall, the kraft-paper honeycomb sandwich panel had better thermal properties and presented lower heat flow, than the gypsum-based drywall, particularly at the interior surface under all scenarios. Although both wall assemblies have a high amount of heat flow at the exterior surface under two scenarios, they showed a lower heat flow at the interior surface under scenario II than the interior surface of both wall assemblies under scenario I. In addition, findings illustrated that wall assembly with kraft-paper honeycomb sandwich panel with an average heat flow of approximately  $21639.1 \text{ W/m}^2$  at the interior performed approximately 4.6% better than gypsum-based drywall with an average heat flow of  $22682.21 \text{ W/m}^2$  under two boundary conditions of medium and high moisture load.

An important concept that is used in the calculation of annual heating energy through the building envelope components is the heating degree days (HDD). HDD is defined as the sum of the difference between the daily average outdoor temperature and a base temperature (typically  $18^\circ\text{C}$ )

over a year for days when the average temperature is lower than the base temperature [35]. In addition, the design characteristics and the building envelopes, and in particular by the overall heat transfer coefficient (U-value) and the area of the walls are effective in determining the annual heating energy load. Therefore, the annual heating energy of a building is calculated according to the following equation (10) [36]:

$$Q = U \times A \times \text{HDD} \times \frac{24}{1000} \quad (10)$$

Where the Q is annual heating energy (kWh), U is the heat transfer coefficient (W/m<sup>2</sup>K), A is the surface area (m<sup>2</sup>), and HDD is the annual heating degree days.

The annual HDD for Ottawa which is located in climate zone 6 is 4600 [37]. According to the WUFI calculations, the U-values of the reference wall and multilayer sandwich panel are 0.179 W/m<sup>2</sup>K and 0.171 W/m<sup>2</sup>K, respectively. Therefore, according to the equation, for the surface area of 1 m<sup>2</sup> of both wall assemblies, the annual heating energy of the reference wall and multilayer sandwich panels is 19.76 kWh and 18.88 kWh, respectively, indicating that the kraft paper honeycomb sandwich panel's energy consumption is lower than the gypsum-based drywall in a year. Based on the results, the difference in annual heating energy load between two wall assemblies is 0.88 kWh. Following that, considering the surface area of a typical house in Canada is roughly 200 m<sup>2</sup>, the developed multilayer sandwich panel with kraft paper honeycomb consumed less energy (approximately 180 kWh. m<sup>2</sup>) compared to the conventional drywall assembly per household.

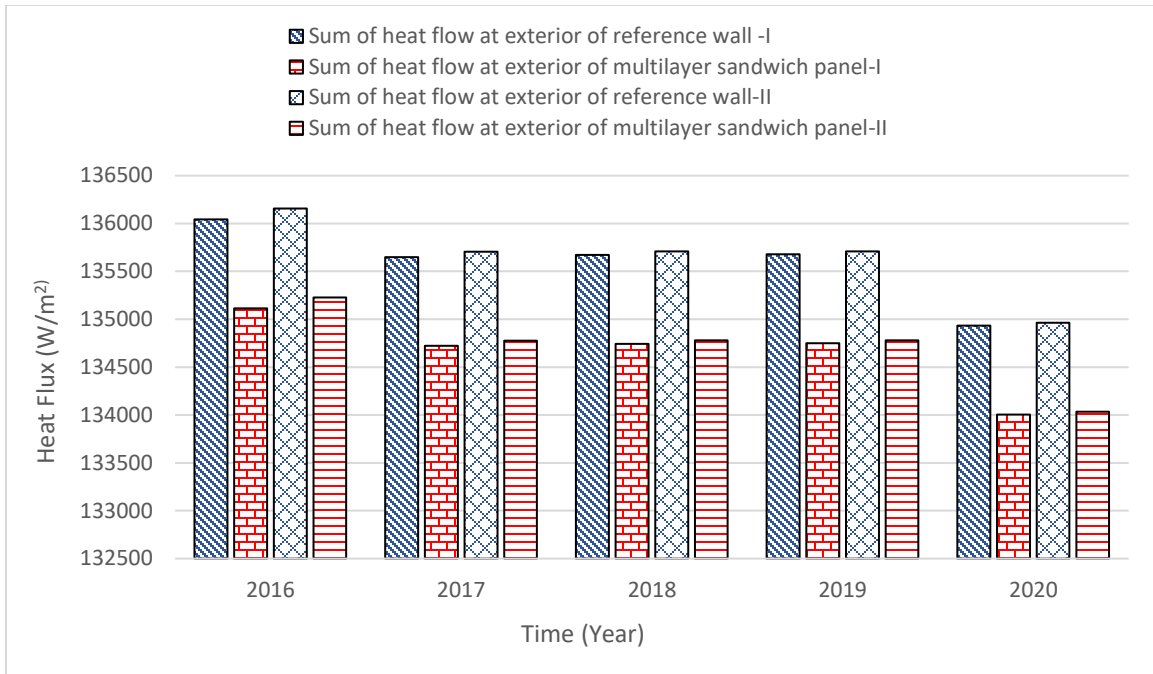


Figure 5.9. Annual heat flow of exterior surface of the reference wall and multilayer sandwich panel under the scenarios I and II.

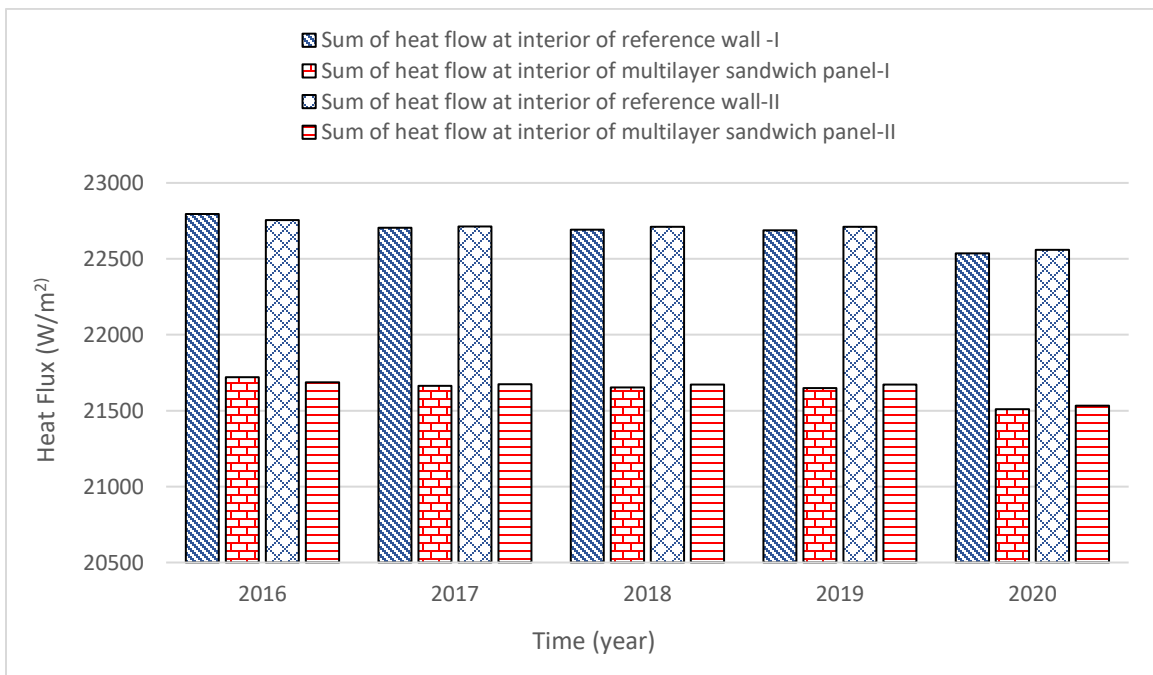


Figure 5.10. Annual heat flow of interior surface of the reference wall and multilayer sandwich panel under the scenarios I and II.

## 5.5. Discussion

Comparison of hygrothermal performance of the reference case composed of gypsum-based drywall with a multilayer sandwich panel made of kraft paper honeycomb reveals substantial improvements using the new sandwich panel for interior wall applications. The water content of individual layer of kraft paper honeycomb sandwich panel with an average of  $0.65 \text{ kg/m}^3$  under scenario I and  $0.95 \text{ kg/m}^3$  under scenario II are significantly lower than that of the gypsum board with an average value of  $4.02 \text{ kg/m}^3$  under scenario I and  $4.91 \text{ kg/m}^3$  under scenario II, respectively. Because the water content adsorption of a porous hygroscopic material is mainly dependent on the distribution of material aperture, the pore volume and adsorption rates increase by increasing the specific surface area. Therefore, the gypsum-based drywall with higher porosity of  $0.706 \text{ m}^3/\text{m}^3$  compared to the kraft paper honeycomb sandwich panel with a porosity of  $0.55 \text{ m}^3/\text{m}^3$  absorbed more water. The results show that similar to previous studies that the water content of gypsum board with the addition of different porous materials such as expanded perlite, and expanded vermiculite was higher compared to the gypsum board without any addition of porous materials [16]. In addition, another possible reason for the lower water content of the kraft paper honeycomb sandwich panel is the replacement of gypsum board with an initial water content of  $8.65 \text{ kg/m}^3$  with layers of flax fiber reinforced cementitious panel, silicone-based adhesive, and kraft paper honeycomb with an initial water content of  $1.8 \text{ kg/m}^3$ . Moreover, the findings illustrate that as different indoor conditions of medium and high moisture load could significantly affect the hygrothermal performance of the wall assembly and specifically on the interior surfaces with direct contact, the inner layers of the reference wall and multilayer sandwich panel have lower water content under scenario I due to the low indoor relative humidity, which ranges between 30% and 60% in comparison to scenario II with an indoor relative humidity ranges between 40% and 70%. In terms of relative humidity, the monitor position of 0.0034 m where the oriented strand board is located in both walls showed high relative humidity in the winter and approximately low relative humidity in the summer due to the higher water vapor diffusion resistance factor and water storage capacity. Although the interior surface of both wall assemblies had similar values of relative humidities, the relative humidity of the gypsum-based drywall is moderately higher than the kraft paper honeycomb sandwich panel. The hygroscopic properties of each material such as moisture storage function and water vapor diffusion resistance factor are considered as effective factors in determining the amount of moisture stored in each assembly as well as the moisture transport rate.

In addition, a hygroscopic material absorbs moisture from the air until a specific equilibrium moisture content which corresponds to the humidity of the ambient conditions is reached. Therefore, as the OSB sheathing and gypsum-based drywall are hygroscopic, their level of moisture content is dependent on the relative humidity of the air contained in the pores. In effect, the level of moisture content of the hygroscopic wall components increases as the water molecule's polarity allows it to bond to the pore surfaces of the materials. The material's storage capacity and the length of the time that moisture can be stored are considered important factors for structures' durability. Therefore, the multilayer sandwich panel with kraft paper honeycomb showed low relative humidity due to the lower porosity compared to the reference case with gypsum-based drywall. In addition, the results reveal that the different indoor conditions (different relative humidities) had a considerable impact on the moisture performance of the wall assemblies and should be taken into account when designing the building envelope.

Isopleth analysis allows the assessment of conditions of high temperature and high relative humidity at the same time that can contribute to mold growth on some building materials. Condensation and mold growth could occur when the dew point temperature of the building material contacting with the air is higher than the temperature. The internal surface condensation in the inner wall assembly can be considered an essential factor in decreasing the structure's durability. High indoor temperature compared to the outdoor temperature, different indoor sources, and lack of ventilation could lead to moisture accumulation. According to the results, as the relative humidity of the interior surface of the reference wall and multilayer sandwich panel is below the relative humidity of 80% limiting isopleths, no mold growth is observed. However, because the mold isopleths of the individual layer of gypsum board under the condition of the cold year of Ottawa with medium moisture load lies above the limiting isopleths, condensation and mold growth are expected due to the higher amount of moisture content stored in the pores compared to the kraft paper honeycomb sandwich panel.

The results also indicate that both wall assemblies had lower heat flow at the interior surface under scenario II compared to the scenario I. The likely reason for decreasing heat losses at the interior surface of the sandwich panel is the replacement of gypsum-based drywall with cementitious panels and kraft paper honeycomb core with low thermal conductivity. The thermal conductivity of hygroscopic materials is proportional to the amount of air replaced by water in the pores. Water's thermal conductivity (580 mW/mK) is more than 20 times that of dry air's thermal conductivity

(25 mW/mK); as a result, even a small increase in water content is expected to result in a significant increase in the thermal conductivity of hygroscopic materials. Therefore, the reference wall with gypsum-based drywall with higher thermal conductivity of 0.16 W/mK conducted more heat compared to the multilayer sandwich panel with kraft paper honeycomb sandwich panel with thermal conductivity of 0.092 W/mK. In addition, the "overall heat transfer coefficient," also known as U-value, is a measurement of how well components of a building envelope transfer heat. In other words, the low U-values indicate the low levels of heat transmittance and the high thermal performance of the building components. Therefore, the multilayer sandwich panel with a U-value of 0.171 W/(m<sup>2</sup>K) presented a lower annual heat flow compared to the reference case with a U-value of 0.179 W/(m<sup>2</sup>K).

## **5.6. Conclusion**

This study focused on evaluating the long-term hygrothermal performance of two selected wall structures made of kraft-paper honeycomb sandwich panel and conventional gypsum-based drywall based on thermal and hygric numerical simulation. The impact of boundary conditions, long-term moisture performance, humidity levels, mold growth potential, and heat flow of two designed wall assemblies were investigated. In this regard, two scenarios of a cold year of Ottawa with medium and high moisture load were considered for the simulation. The results presented that both wall assemblies performed well in all hygrothermal characteristics. In addition, the monthly average water content of both wall assemblies decreased over the simulation period, demonstrating that wall structures were dried out. The findings indicated that the multilayer sandwich panel with kraft paper honeycomb had a lower water content than the reference wall with an average value of 0.65 kg/m<sup>3</sup> under scenario I and 0.95 kg/m<sup>3</sup> under scenario II. Moreover, the internal layers of gypsum board and kraft paper honeycomb showed lower water content under scenario I than scenario II due to the lower relative humidity. Furthermore, while the water content of the kraft paper honeycomb sandwich panel in scenario II was higher than that of scenario I, it was lower than that of gypsum-based drywall due to the lower initial water content of different layers of flax fiber reinforced cementitious panel, silicone-based adhesive, and kraft paper honeycomb.

In terms of mold growth, the different indoor conditions (different relative humidities) are effective on the moisture performance and condensation risk of the wall assemblies. The findings revealed that although individual layers of both wall assemblies had similar relative humidity values under both conditions, the multilayer sandwich panel showed approximately lower relative humidity than the reference wall under two scenarios due to the lower absorption of water content. In addition, because the relative humidity of the reference case and multilayer sandwich panel is lower than the relative humidity of limiting isopleths of 80%, no mold growth and condensation is occurred. Regarding thermal performance, due to the lower thermal conductivity of cementitious panels and kraft-paper honeycomb, the multilayer sandwich panel performed roughly 4.6% better and exhibited lower annual heat flow with an average of  $21639.1 \text{ W/m}^2$ , particularly at the interior surface, compared to the reference wall assembly with an average heat flow of  $22682.21 \text{ W/m}^2$  under two scenarios. In addition, For the equal surface area of both wall assemblies, the multilayer sandwich panel with a smaller u-value showed a lower annual heating energy load compared to the reference wall. Following that, as the efficiency of the envelope is frequently discussed in terms of the thermal properties in heat transfer, the multilayer sandwich panel is more energy-efficient than the reference wall with gypsum-based drywall over the calculation period.

## **5.7. Limitations and Future Research**

Future research is recommended to expand the understanding of the long-term hygrothermal performance of kraft paper honeycomb sandwich panels as an interior wall application. The study's limitations that point to the need for future work and investigation are as follows: The material properties of the gypsum-based drywall used in the analyses are driven from the WUFI database. Therefore, future work should also include further experimental testing of gypsum-based drywall characteristics to provide comprehensive modeling results. In addition, future research should also investigate different types of adhesives and cementitious panels with better physical and mechanical properties to have a better understanding of the hygrothermal properties of the kraft paper honeycomb sandwich panel. Finally, further numerical analysis is required to evaluate different wall assembly design configurations using the developed sandwich panel with additional combinations of indoor and outdoor boundary conditions.

## 5.8. References

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## CHAPTER 6

### **6. Concluding Remarks**

#### **6.1. Conclusions**

This research study investigated and compared the physical and mechanical properties and hygrothermal performance of a new sandwich panel with gypsum drywall. The sandwich panel is developed using locally resourced materials such as kraft paper and cementitious materials. The new sandwich panel has given a chance to use local materials which are cheaper and have less environmental impact. The mechanical and physical performance of the sandwich panel was investigated through experimental testing of specimens considering different cementitious mix designs and core thicknesses. The purpose of this work was to improve the thermal and mechanical performance of the new sandwich panel while reducing environmental impacts to replace gypsum drywall. The hygrothermal analysis included one-dimensional computer modeling investigating the performance of wall assemblies consisting of gypsum drywall and kraft paper honeycomb. The modeling was performed for two boundary conditions of medium and high moisture load in Ottawa for five consecutive years. As a result, this study contributes new knowledge and information about the potential of kraft paper honeycomb sandwich panels to be effectively used as the interior surface of wall assemblies under Canadian weather conditions.

The experimental portion of this study indicated that the new sandwich panel showed better physical and mechanical properties compared to the gypsum drywall. The results presented that flexural strength and stiffness of the cementitious mix designs with the addition of flax fibers were increased substantially, with respect to the core thickness. Flax fibers are effective in reinforcing the cementitious plates by increasing the cracking resistance and following that enhancing the flexural strength of the sandwich panels. In addition, as the modulus of elasticity of the material and the geometry of the structure in terms of the planar moment of inertia are key

factors in determining the stiffness of the sample, higher stiffness was observed in thick samples in which layers are located further away from the motion axis.

In addition, as the samples with thicker cores have larger void volume and higher average volume, their density is significantly lower than that of samples with thinner cores. Therefore,  $\text{Flax}_{\text{thick}}$  samples resulted in exhibiting lower densities compared to  $\text{Flax}_{\text{thin}}$  specimens. The use of the thicker kraft paper honeycomb core resulted in an increase in the void volume entrapped in the honeycomb core. Therefore, as the thermal conductivity of air is lower than that of kraft paper honeycomb, the sandwich panel's thermal conductivity decreased. Moreover, because the thermal conductivity of a material is inversely proportional to the thickness, the sample with a thicker core presented a higher decrease in heat conduction. Based on the water vapor transmission results, the samples with flax reinforced plates and a thicker core experienced lower rates of water vapor transmission compared to the flax samples with a thinner core. The likely reason is that as the core thickness of the specimen increases, more moisture is absorbed due to the higher capacity. Therefore, flax fiber samples with a thicker core showed a greater decrease in the rate of water vapor diffusion. In addition, as the permeance is directly proportional to water vapor transmission rate and inversely related to the thickness,  $\text{Flax}_{\text{thick}}$  had lower permeance in comparison to  $\text{Flax}_{\text{thin}}$ .

WUFI calculation presented that both reference wall and multi-layer sandwich panel performed well in all hygrothermal characteristics. However, the results illustrated that the total water content of the individual layer of kraft paper honeycomb is significantly lower than that of gypsum board under two scenarios. The possible explanation is the lower initial water content of the layers of flax fiber reinforced cementitious panel, silicone-based adhesive, and kraft paper honeycomb. Because the pore volume and adsorption rates of porous hygroscopic material are primarily determined by the distribution of material aperture, increasing the specific surface area increases the water content adsorption. As a result, the gypsum-based drywall with higher porosity absorbed more water than the kraft paper honeycomb sandwich panel. Following that, the hygroscopic gypsum drywall absorbed more moisture content from the air until it reached a specific equilibrium moisture content corresponding to the humidity of the ambient conditions compared to the multilayer sandwich. Therefore, the relative humidity of the gypsum-based drywall is slightly higher than that of the kraft paper honeycomb sandwich panel. However, as

the relative humidity values of both wall assemblies were below the mold growth threshold of 80% during the calculation period under two scenarios, no mold accumulation is observed.

The thermal conductivity of hygroscopic substances is dependent on the amount of air replaced by water in the pores. Because the thermal conductivity of water is more than 20 times that of dry air, even a small increase in water content is resulted in a substantial increase in hygroscopic thermal conductivity of materials. As a result, the reference wall with gypsum-based drywall presented higher thermal conductivity compared to the multilayer sandwich panel with kraft paper honeycomb sandwich panel. Moreover, the replacement of gypsum drywall with cementitious panels and kraft paper honeycomb with lower thermal conductivity resulted in lower annual heat flow and better thermal performance under two scenarios. As the level of heat transmittance and annual heating energy is related to the overall heat transfer coefficient (U-value), the multilayer sandwich panel with a lower u-value of 0.171 W/(m<sup>2</sup>K) exhibited lower annual heating energy load than the reference wall with a U-value of 0.179 W/(m<sup>2</sup>K).

## **6.2. Limitations and Recommendations for Future Work**

This research provided an insight into the behavior of kraft paper honeycomb sandwich panels such as flexural strength, thermal conductivity, and numerical modeling. However, further research is required to fully understand the performance of the sandwich panel and find all the missing properties. The following are the study's limitations, which indicate the need for further research and investigation:

- This study used all-purpose multi-usage silicone-based adhesive to attach the core to the cementitious panels. Therefore, future work should use different types of adhesives to evaluate and improve the hygrothermal performance of the sandwich panel. In addition, the recycling of materials that are natively produced throughout other industries in Canada such as slag, fly ash, and flax fibers in combination with naturally occurring materials such as kaolin and lime will provide an opportunity to create an optimal solution for the objectives of increased R-Value, sound absorption, strength and water resistance over traditional drywall. Therefore, future work should also include different types of face sheets to improve the mechanical and physical properties of the sandwich panel.

Moreover, future work should focus on considering treatments to enhance the moisture absorption properties of the kraft paper honeycomb core.

- Developing sandwich panels manually and through using molds can result in increasing the variability of the samples as the dimensions are not possible to be constant. Therefore, Future work should focus on improving the repeatability of the samples through considering automatic processing techniques such as 3D printing.
- Additional hygrothermal experimental analysis, such as an investigation of the moisture buffer capacity of the developed sandwich panel, should be considered in future research.
- Future research should focus on determining some other behaviors sandwich panel experimentally to apply in WUFI pro software for the validation of the developed models and investigating a better and more comprehensive numerical analysis. In addition, as the material properties of the gypsum-based drywall are generated from the WUFI database, future work should include further experimental testing of gypsum-based drywall characteristics to provide comprehensive modeling results.
- More numerical analysis is required to investigate and compare different wall assembly design configurations, with the developed sandwich panel under different combinations of inside and outside boundary conditions.

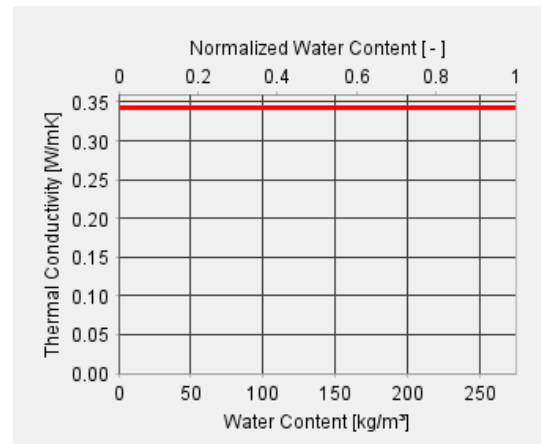
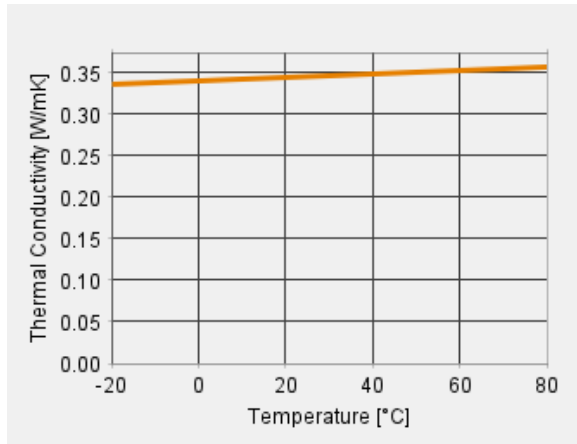
## 7. APPENDICES

### 7.1. Appendix A: Physical Properties of Materials Used in WUFI

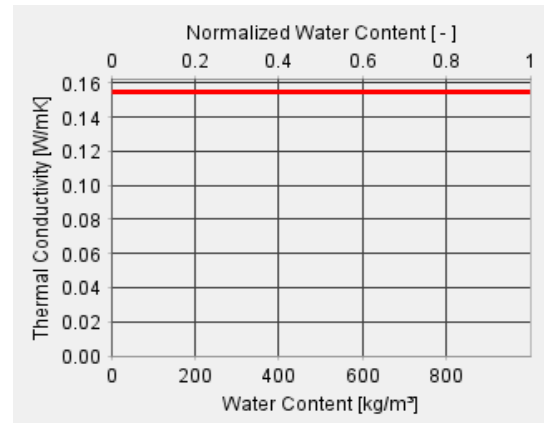
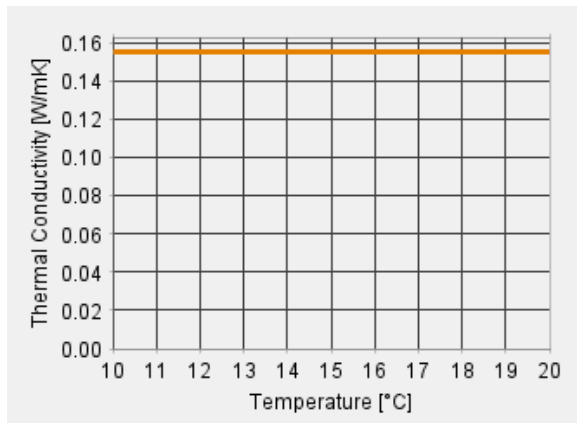
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#### 1. Thermal conductivity functions

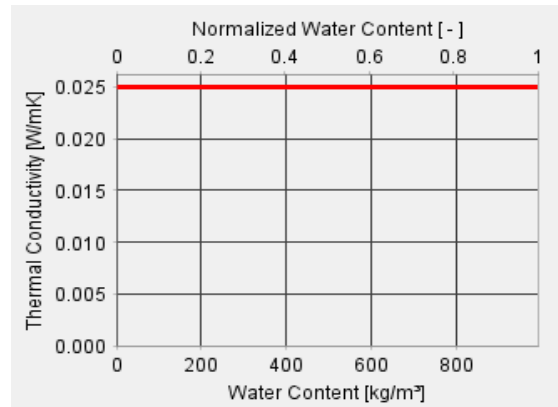
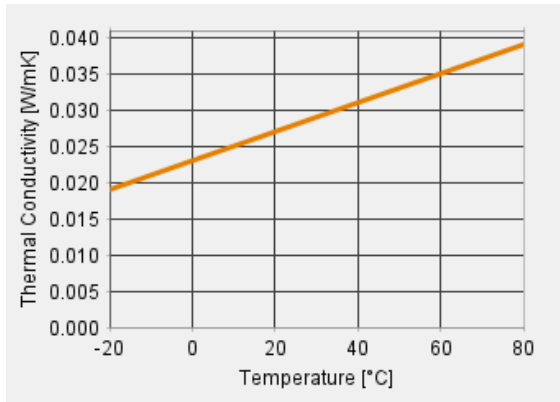
##### A. Regular Lime Stucco



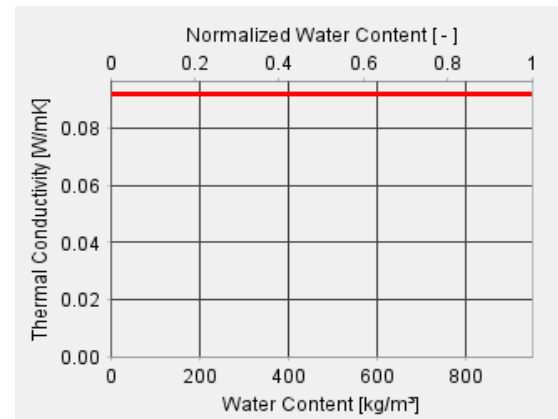
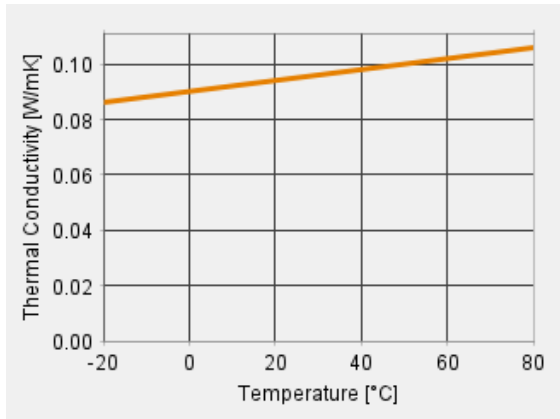
##### B. Air Layer



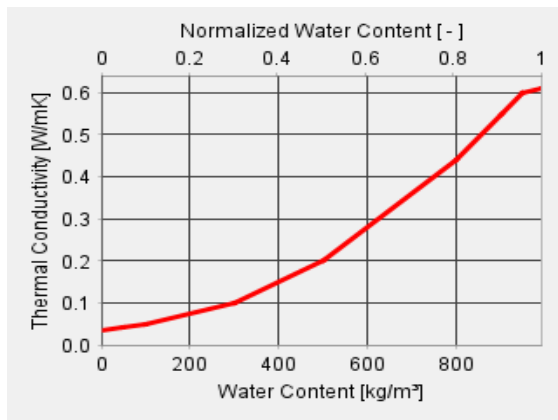
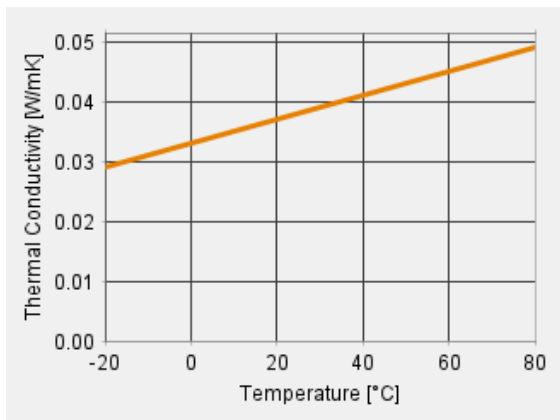
### C. Extruded Polystyrene Insulation



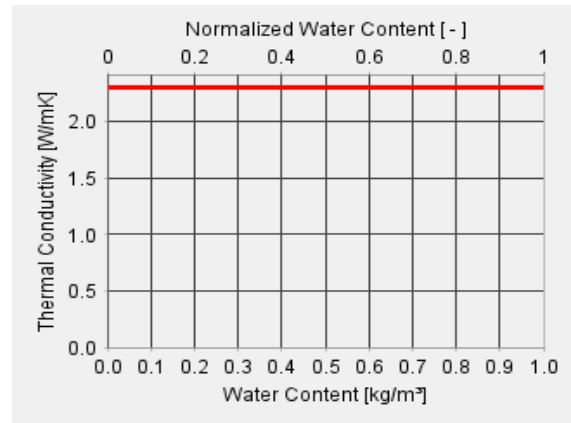
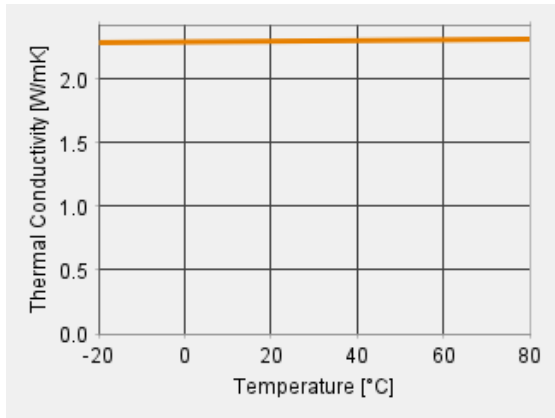
### D. Oriented Strand Board



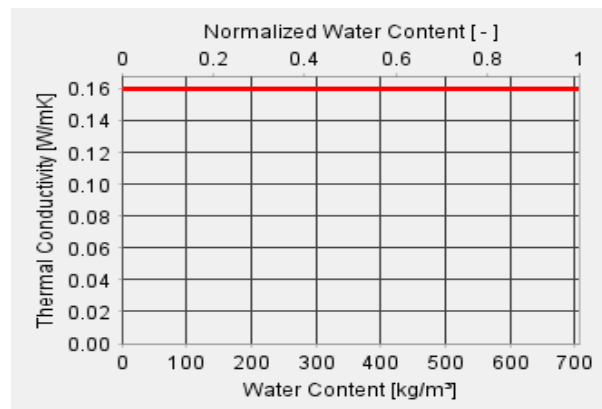
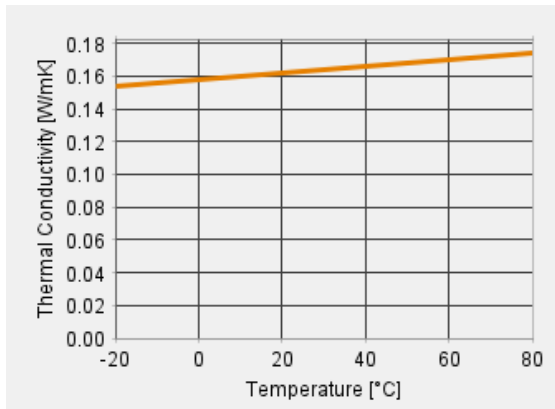
### E. Fiber Glass



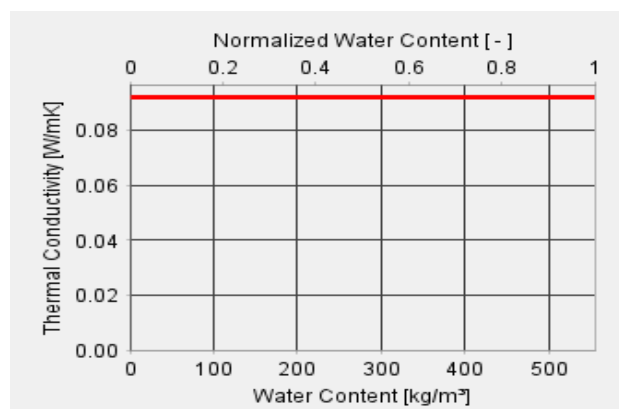
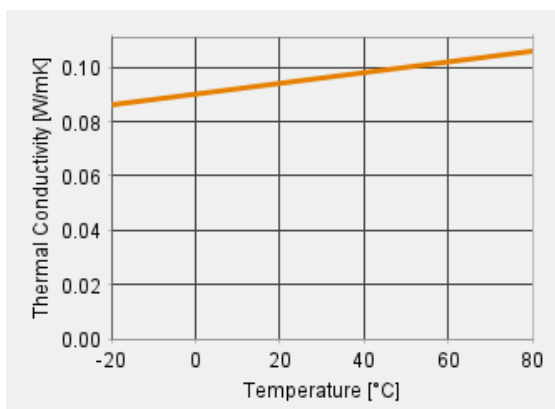
## F. Vapor Retarder



## G. Interior Gypsum Board

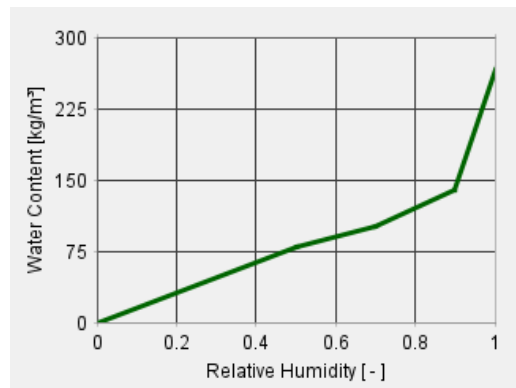


## H. Kraft Paper honeycomb

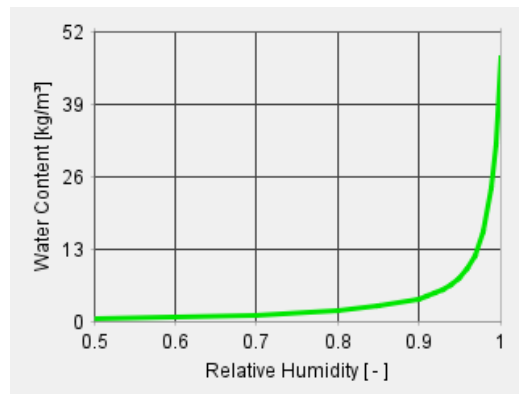


## 2. Moisture storage functions

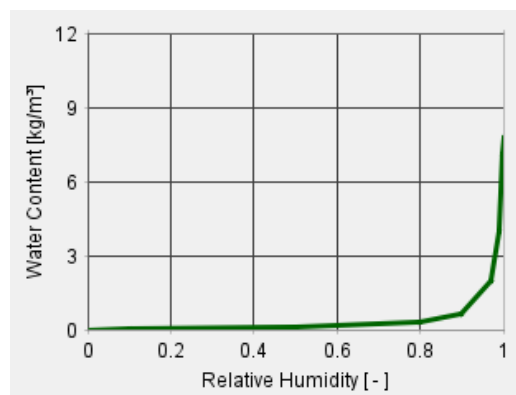
### A. Regular Lime Stucco



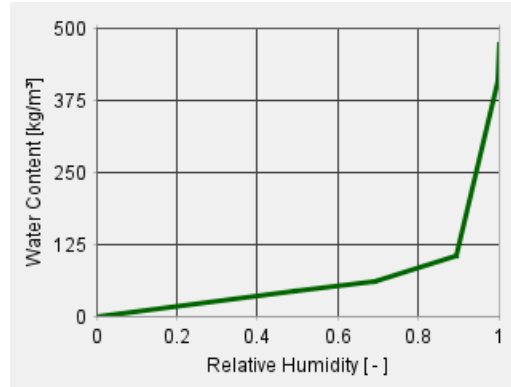
### B. Air Layer



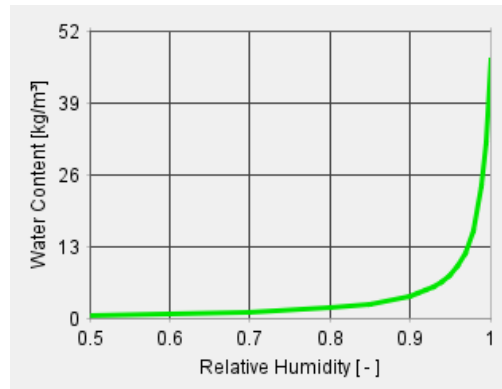
### C. Extruded Polystyrene Insulation



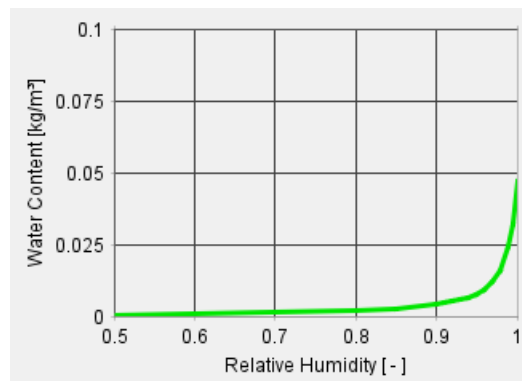
### D. Oriented Strand Board



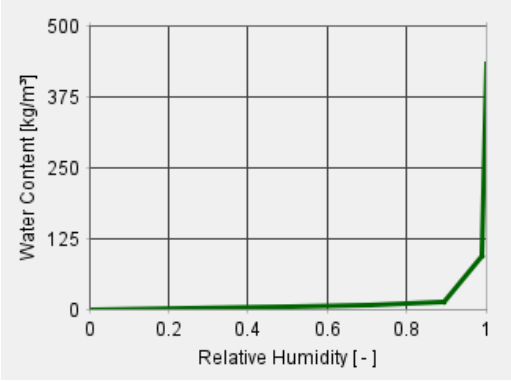
### E. Fiber Glass



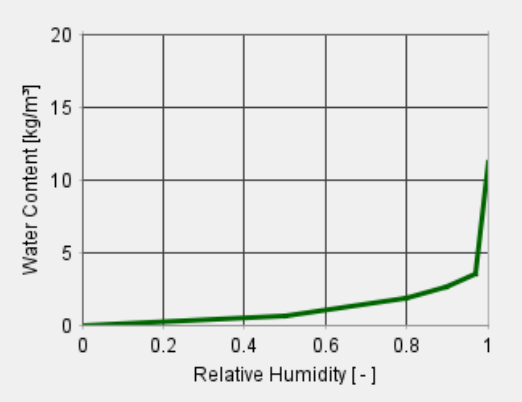
### F. Vapor Retarder



G. Interior Gypsum Board



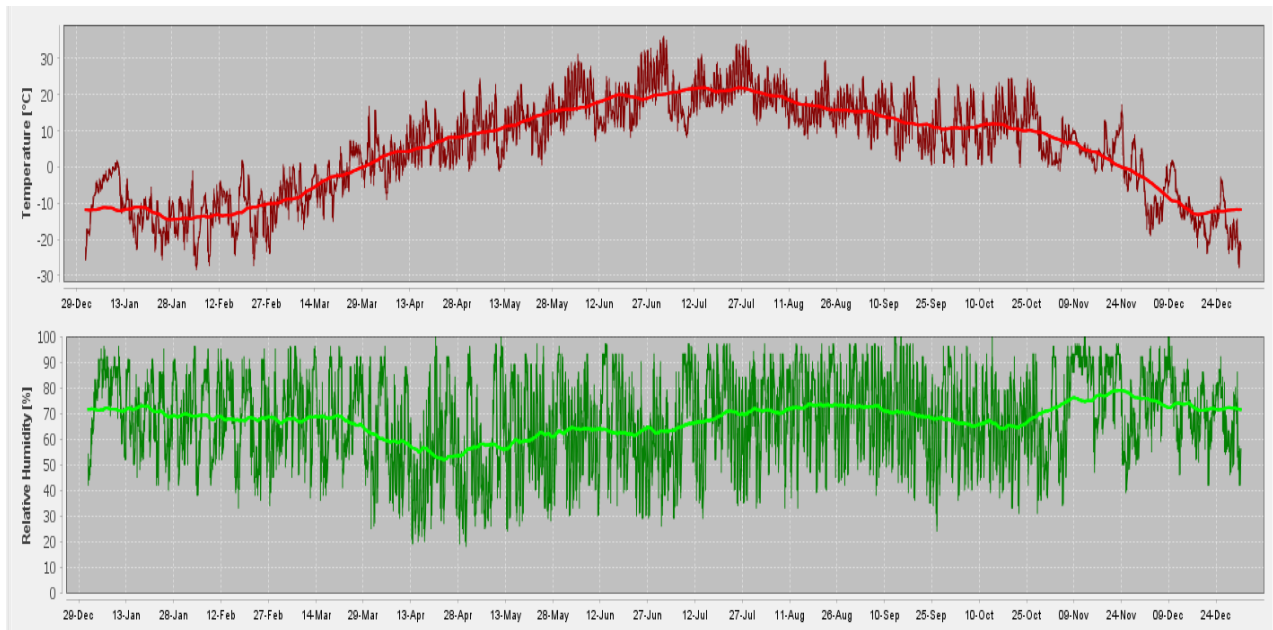
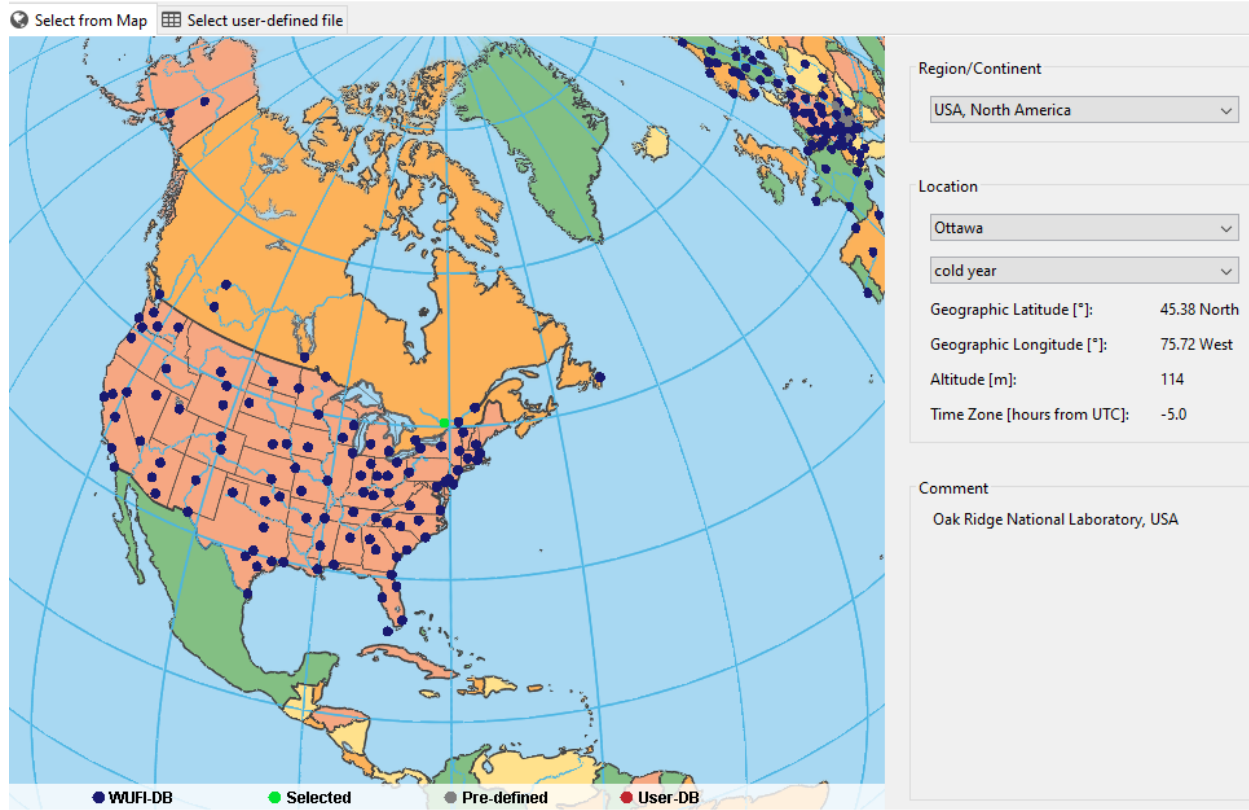
H. Kraft Paper honeycomb



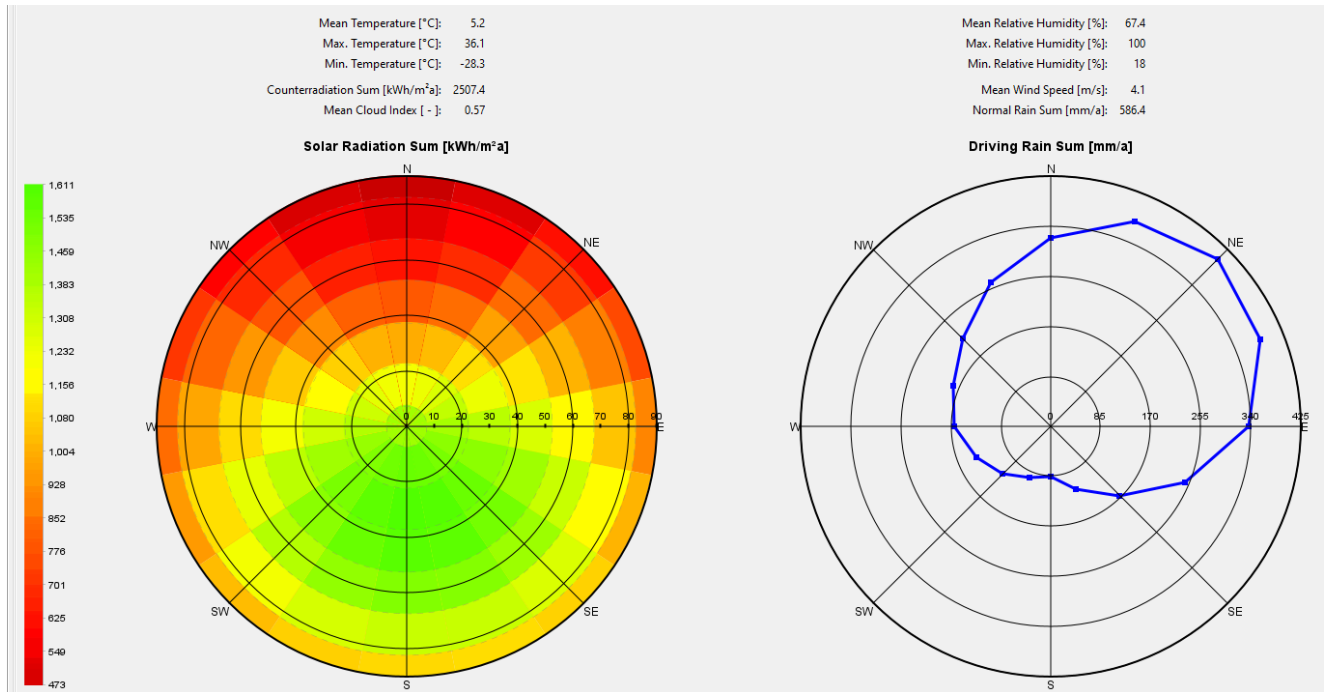
## 7.2. Appendix B: Indoor and Outdoor Boundary Conditions

### 1. Outdoor Conditions

#### A. Cold year of Ottawa

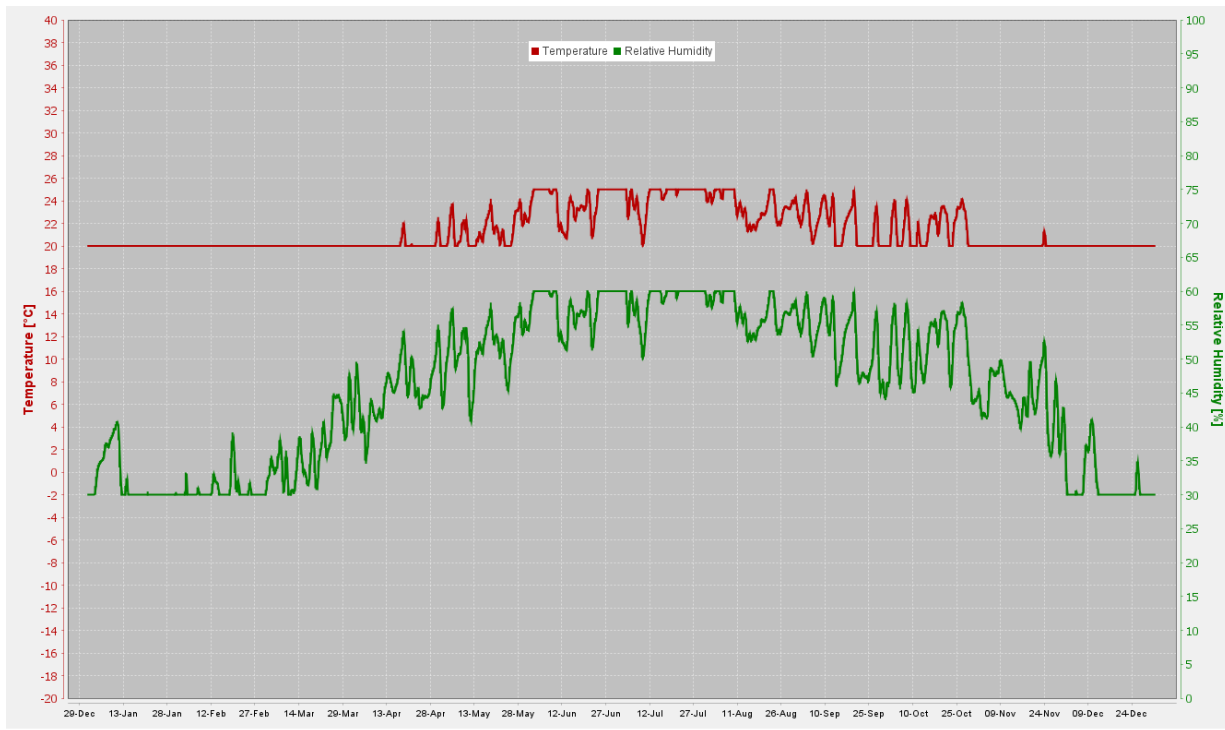


# Climate analysis



## 2. Indoor conditions

### A. Medium moisture load



B. High moisture load

