Hygrothermal performance of a new composite sandwich panel alternative to gypsum drywall

Sepideh Shahbazi[1], Miroslava.Kavgic[1], Reza Foruzanmehr [1]
[1] Department of Civil Engineering, University of Ottawa, 161 Louis Pasteur, Ottawa, ON K1N 6N5, Canada

Abstract

The most common type of drywall is not water-resistant. Thus, it can be prone to water and moisture damage, ultimately leading to mold formation in poorly insulated and highly occupied buildings in Canadian climates, such as remote indigenous communities. This study investigates the hygrothermal performance of a new sandwich panel made of a Kraft paper honeycomb core layer bonded with two cementitious face sheets. Two variations of a typical wall with gypsum drywall and a proposed sandwich panel were modeled in WUFI and compared under cold and high moisture load boundary conditions over the five years. The results show that the proposed sandwich panel had significantly lower moisture content and better thermal performance of approximately 4.6% than the drywall panel.

Introduction

Moisture, thermal comfort, and indoor air quality are essential considerations in developing energy-efficient buildings [1]. Interior humidity is one of the principal factors affecting the indoor environmental quality and durability of a building's materials [2]. Indoor moisture can arise from a variety of sources, including 1) indoor activities [3], 2) groundwater intrusion and precipitation penetration [4], and 3) building design and operational difficulties such as uncontrolled airflows [5]. Moisture control has become a worldwide issue due to changes in building operations and construction techniques [6]. The moisture problems in buildings may result in the hygrothermal performance of building materials by creating problems such as mold growth, condensation, and loss of thermal performance [7,8,9]. In addition, hazardous compounds emitted from internal building materials throughout the manufacturing and construction process may impact indoor air quality [9].

Gypsum and gypsum-derived products such as drywall have been widely used as construction materials since the early 1900s due to their abundance of primary ingredients [1,2]. Gypsum boards offer ease of execution, low cost, and fire resistance. Nevertheless, they have drawbacks such as high thermal conductivity, poor moisture and water resistance, and a negative environmental impact [10]. Therefore, functional building materials with improved hygrothermal characteristics are required to offer healthy indoor air quality by regulating water vapor.

Sandwich structures, defined as multi-layered composite structures, are becoming more popular as structural building components in the construction industry due to their high stiffness-to-weight ratio, energy efficiency, and improved thermal and acoustical qualities [11,12,13]. A typical sandwich panel comprises two thin and stiff outer faces and one low-density material core placed between the faces. Non-cementitious materials such as ceramics, aluminium, and wood are common for face sheets [14]. Regarding cores, rigid foamed materials such as polyurethane, polyisocyanurate, and polystyrene are mainly considered because of their low thermal conductivity and high moisture resistance [14]. However, because foam plastics constitute environmental hazards [15], materials such as kraft paper honeycomb represent viable alternatives.

In this respect, a previous study offered a cementitious kraft-paper honeycomb sandwich panel with improved mechanical and physical properties to solve the drawbacks of gypsum-based drywall [16]. The honeycomb sandwich panel consists of a core layer of low-density kraft-paper honeycomb glued to high-density outer facing sheets of the cementitious board with flax fibers due to their outstanding mechanical capabilities, high fire resistance, and minimal environmental effects. Furthermore, because the flax fiber-reinforced kraft paper honeycomb samples developed fewer cracks for water molecules to permeate inside the panel, they demonstrated a lower water vapor transmission rate and a more substantial decrease of 42% of thermal conductivity than gypsum-based drywall [16]. Although flax fiber-reinforced kraft-paper honeycomb cementitious sandwich panels outperformed gypsum-based drywall, this study did not investigate the sandwich panel's long-term hygrothermal behavior.

Furthermore, predicting long-term hygrothermal performance is essential for increasing the assembly's durability over its service life [17].

This research aims to fill this knowledge gap by comparing the hygrothermal performance of a wall assembly with a kraft-paper honeycomb cementitious sandwich panel and a standard gypsum-based drywall assembly in the Canadian climate. In this regard, the one-dimensional moisture performance simulation tool of WUFI Pro 6.5 was used to determine the building components' hygrothermal performance [18]. The numerical simulation analysis provides an opportunity to expand on the experimental findings from the prior study. Furthermore, in this study, the numerical analysis was carried out for both wall assemblies over five years, from January 1, 2016, to December 31, 2020. The output contains useful information such as the water content of each layer, relative humidity, monitor position isopleths, and heat flow.

Simulation Parameters

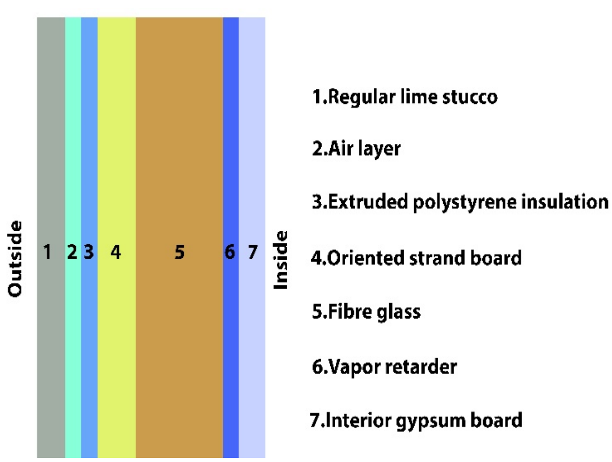
Wall Assembly Configurations

The National Energy Code for Buildings (NECB) specifies technical requirements for energy efficiency in the design and construction of new buildings and improvements to existing structures [19]. The NECB requirements can be considered as the minimum acceptable measures, such as the minimum effective R-value requirements for Canada's various temperature zones to achieve the above-listed objective [19]. According to the NECB code, Ottawa is in zone 6 (4000 to 4999 HDD), where the minimum R-value standard for building enclosure assemblies is 3.08 m^2k/W for the above-grade wall assemblies [20]. This study followed this performance requirement to design two types of wood-frame wall assemblies: 1) reference wall and 2) multilayer sandwich panel. The reference wall is designed based on a Canadian conventional wall assemblies literature review. Thus, the reference wall comprises traditional 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 design of a multilayer sandwich panel is based on the standard techniques defined in ASTM C305 "Standard Practice for Mechanical Mixing of Hydraulic Cement Pastes and Mortars of Plastic Consistency" [16]. Therefore, the multilayer sandwich panel comprises traditional 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 1 presents the composition of the designed assemblies in WUFI Pro.

Experimental data and the WUFI database were utilized to derive the physical parameters of all materials used in simulations. In this respect, traditional 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 section on generic materials. The layers of extruded polystyrene insulation, fiberglass, and vapor retarder were available in the North American database's insulation materials and membranes section. The properties of OSB and interior gypsum boards were taken from the North American database's building boards and sidings section. Experimental data were used to quantify the developed sandwich panel's thermal conductivity, porosity, bulk density, specific heat capacity, and water vapor diffusion resistance. According to the information selected in WUFI software, the reference case with an R-value of 5.41 m^2K/W and multilayer sandwich panel with an R-value of 5.66 met Ottawa's minimum defined code requirements. The main material parameters anticipated for drywall assembly and kraft paper honeycomb sandwich panel are summarized in table 1.

Boundary Conditions

To redirect the content into its starting value and follow the flow cycle throughout the year, the initial conditions of the materials should be established in WUFI Pro software [21]. Based on the WUFI collection and literature, Table 2 depicts the initial conditions applied to the materials of the assemblies.



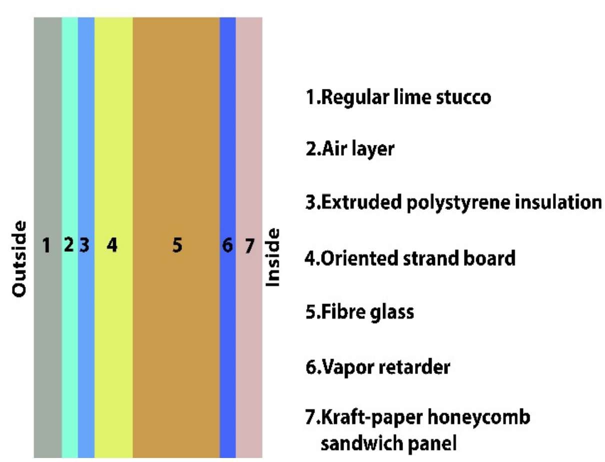


Figure 1. The composition of 1) reference wall 2) multilayer sandwich panel for numerical modelling.

Table 1. Material properties of drywall assembly used in numerical analysis.

Property	**Thickness [m]**	**Bulk Density [kg/m^3]**	**Porosity [m^3/m^3]**	**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

Table 2. initial properties of materials.

Material	Temperature °C	Water Content [kg/m^3]	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	

The South-East orientation, which is the compass direction in which the building component faces, was considered in this study to maximize the combination of solar exposure. Both wall components were placed with 90° inclination and a short height of 10 m for driving rain coefficients. For the heat resistance of both exterior and interior surfaces, default values were chosen for surface transfer coefficients. The heat resistance of the exterior surface (left side) was 0.0588 (m^{2}K)/W without wind dependency. The internal surface heat resistance (right side) was 0.125 (m^{2}K)/W. The exterior surface employed for solar heating from the visible light spectrum had a short-wave radiation absorptivity of 0.4, which corresponded to the stucco, a typical bright setting [22]. Regarding the sd values, describing the diffusion resistance of the layer in terms of thickness, no surface coating was considered on both sides of the wall enclosures. A consecutive five-year calculation period (from January 1, 2016, to December 31, 2020) was used to analyze the long-term hygrothermal performance of wall assemblies.

Climate file

WUFI Pro software should define surface boundary conditions to analyze the model for particular interior and outdoor climates. Exterior climate (rain, sun, wind, relative humidity, temperature), interior weather conditions (temperature, relative humidity), and initial moisture contents are all boundary conditions in the one-dimensional WUFI program. The WUFI weather database contains several external and internal climatic boundary conditions that vary depending on location and severity. In this case, both wall assemblies were subjected to two scenarios that combined one external and two internal boundary conditions. The default WUFI climate file of the cold year in Ottawa, Canada, was chosen as an outer environment for simulation. The interior climate was defined using EN 15026, which allows for both medium and high moisture loads in residential buildings. The medium moisture load is related to the normal occupancy of residential and office spaces.

On the other hand, high moisture load characterizes residential dwellings with high occupancy. Furthermore, in this standard, the variation of the indoor air temperature is derived from the variation of the outdoor air temperature using a transfer function. For instance, when the outside temperature is below 10°C, heating or air conditioning maintains a constant 20°C indoor temperature; when the outside temperature is higher, the indoor temperature rises linearly but does not exceed 25°C. The top and bottom surfaces of the designed wall assemblies functioned as an adiabatic or impermeable boundary because heat and moisture are transmitted across the symmetry axis in symmetric components. Table 3 summarizes the selected exterior and internal climatic conditions.

Table 3. Indoor and outdoor environmental boundary conditions.

Scenarios	Outdoor Conditions	Indoor Conditions
Scenario I	**Cold year** Max Temp=36.1 °C Min Temp=-28.3°C Mean Temp= 5.2 °C Max RH= 100 % Min RH= 18 % Mean RH= 67.4 %	**Medium moisture load** Max Temp= 25 °C Min Temp= 20 Mean Temp = 22.5 °C Max RH= 60 % Min RH= 30 %
Scenario II		**High moisture load** Max Temp= 25 °C Min Temp= 20 Mean Temp= 22.5 °C Max RH= 70 % Min RH= 40 %

Results and Discussion

Moisture content

The water content of individual layers is a significant indicator in determining the condensation risk in the assembly [23]. Table 4 presents the average water content of the reference wall and multilayer sandwich panel in mass percent at the start and end of the calculation period. According to the findings, the obtained water contents for both walls are much lower than the practiced standard (20 mass-percent) [24]. As a result, there was no moisture accumulation in the wall assemblies in both cases. Furthermore, in both scenarios, the total average water content of the reference wall and multilayer sandwich panel gradually reduced, indicating that the building envelopes were drying out during the simulation.

Table 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
I	0.662	0.644	0.101	0.098
II	0.805	0.788	0.148	0.142

Figures 2 and 3 show the monthly average total water content of individual layers of the reference wall and multilayer sandwich panel under two scenarios over five years. The results suggest that changing indoor conditions from medium to high moisture loads considerably impacted the hygrothermal performance of the interior surface of the wall assemblies. As a result, in the first scenario, the inner layers of the reference wall and multilayer sandwich panel have a lower water content due to the lower relative humidity and greater indoor air temperatures. Although the water content of the air layer and fiberglass are relatively the same in both wall assemblies under two scenarios, the water content of gypsum board and kraft paper honeycomb sandwich panel was higher in the second scenario than in the first scenario.

In addition, findings indicate that under the first scenario, the average water content of the reference case's interior surface fluctuates between 4.70 kg/m^3 and 2.72 kg/m3, with an average of 4.02 kg/m^3. However, the water content of the multilayer sandwich panel's internal surface ranges from 0.81 kg/m^3 to 0.39 kg/m3, with an average of roughly 0.65 kg/m^3 under the same condition. Moreover, 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. Although surface properties significantly affect absorption rate, porosity determines the total material's absorption rate. In other words, increasing void volume fraction (i.e., porosity) increases specific surface area and thus absorption rate.

As a result, the gypsum-based drywall with a porosity of 0.706 m^3/m^3 absorbed more water than the kraft paper honeycomb sandwich panel with a porosity of 0.55 m^3/m^3.

Furthermore, the replacement of gypsum board with an initial water content of 8.65 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 kg/m^3 could be considered as another reason for the lower water content of the kraft paper honeycomb sandwich panel. In addition, because moisture accumulation and mold growth are primarily determined by water content, no moisture accumulation happened for a long time in both gypsum board and kraft paper honeycomb.

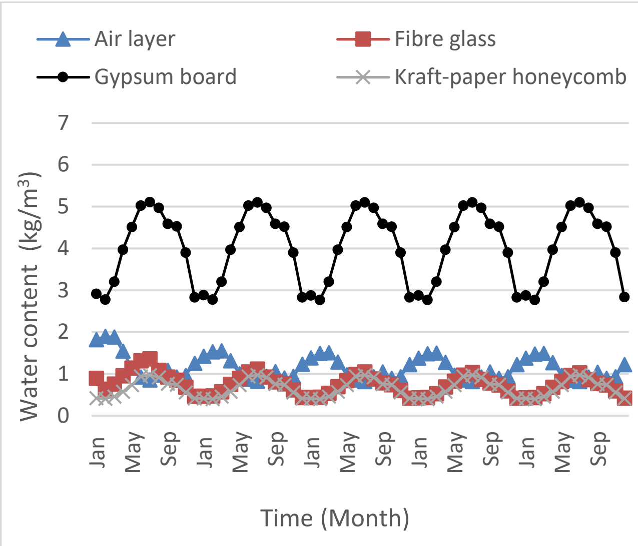


Figure 2. Average monthly total water content distributions of individual layers under scenario I.

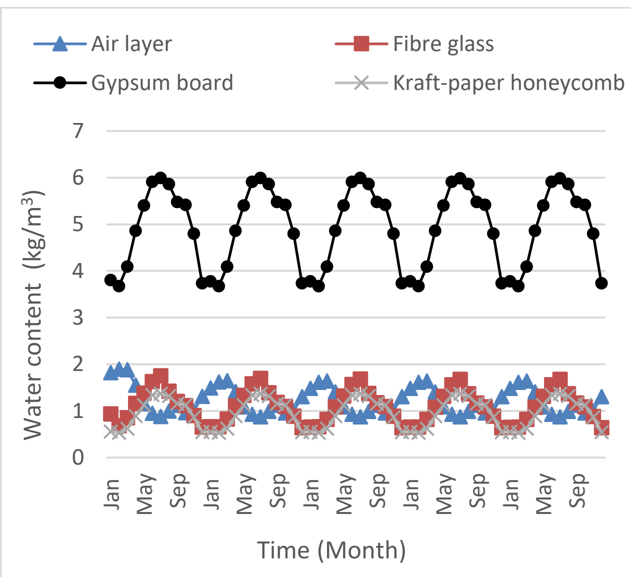


Figure 3. Average monthly total water content distributions of individual layers under scenario II.

Thermal performance of the reference wall and multilayer sandwich panel

Figures 4 and 5 compare the total yearly heat flows on both wall assemblies' interior and exterior surfaces over five years and under two scenarios. Overall, the kraft-paper honeycomb sandwich panel experienced lower heat flow, specifically at the inner surface, than the gypsum-based drywall under both scenarios. The likely explanation for these results is the lower thermal conductivity of the multilayer sandwich panel than the gypsum-based drywall. In this respect, considering that the rate of heat flow through the building envelope is proportional to the wall assembly's U-value, the multilayer sandwich panel with a U-value of 0.171 W/(m^{2}K) had a lower annual heat flow than the reference case with a U-value of 0.179 W/(m^{2}K). Furthermore, under two boundary scenarios of medium and high moisture loads, findings showed that wall assembly using kraft-paper honeycomb sandwich panel with an average heat flow of 21639.1 W/m^2 performed 4.6% more efficiently than gypsum-based drywall with an average heat flow of 22682.21 W/ m^2. Also, even though both wall assemblies have a significant amount of heat flow on the exterior surface under two scenarios, the interior surface of both wall assemblies under scenario II had a lower level of heat flow than the similar cases under the first scenario.

An important concept in calculating annual energy costs through building envelope elements is the heating degree days (HDD). HDD sum the difference between the daily average outdoor temperature and a base temperature (typically 18°C) over a year [25]. In addition, the overall heat transfer coefficient (U-value) and the area of the walls are effective in determining the annual heating energy load. As a result, the annual heating energy of a building is calculated using the equation (1) below:

$$Q = U \times A \times HDD \times \frac{24}{1000} \qquad (1)$$

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

For Ottawa, which is in climate zone 6, the annual HDD is 4600 [26]. According to WUFI calculations, the U-values of the reference wall and multilayer sandwich panel are 0.179 W/m2K and 0.171 W/m2K, respectively. Therefore, the annual heating energy of the reference wall and multilayer sandwich panels for a surface area of 1 m^2 of both wall assemblies is 19.76 kWh and 18.88 kWh, respectively. This result indicates that the kraft paper honeycomb sandwich panel consumes less energy in a year than the gypsum-based drywall.

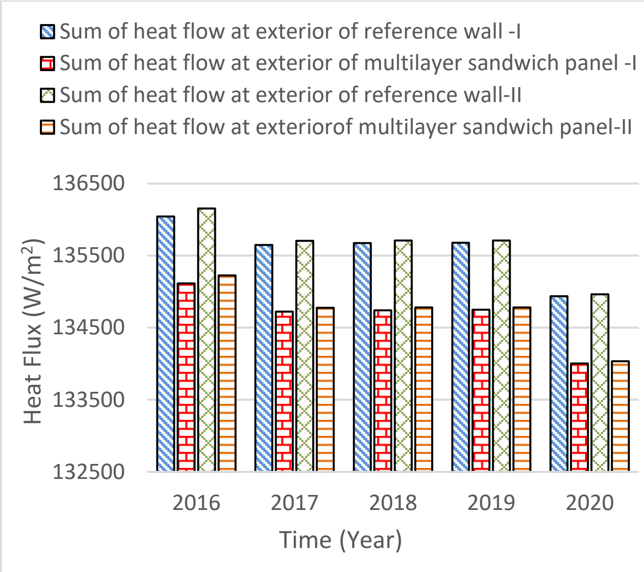


Figure 4. Annual heat flow of exterior surface of the reference case and multilayer sandwich panel under scenarios I and II.

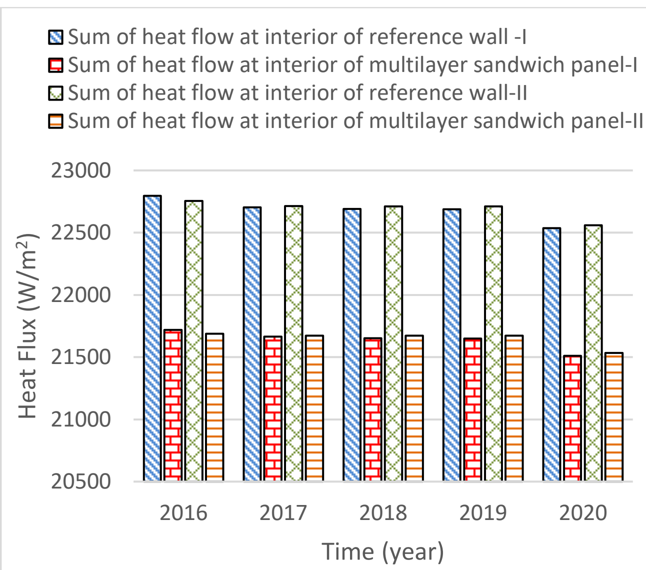


Figure 5. Annual heat flow of interior surface of the reference wall and multilayer sandwich panel under scenarios I and II.

Conclusion

This study investigated the long-term hygrothermal performance of two wall assemblies composed of kraft-paper honeycomb sandwich panel and conventional gypsum-based drywall based on thermal and hygric simulation. In this regard, the impact of boundary conditions, long-term moisture performance, condensation, and mold growth potential of two wall assemblies were studied under two scenarios of the cold year of Ottawa with medium and high moisture loads. The findings indicated that both wall assemblies performed well in all the hygrothermal parameters. Both wall assemblies showed lower water content in the first than the second due to the lower relative humidity. However, the multilayer sandwich panel with kraft paper honeycomb with an average value of 0.65 kg/m^3 under the scenario I presented lower water content than the reference case with gypsum-based drywall. In addition, the overall average water content in mass percent of the reference wall and multilayer sandwich panel under two scenarios gradually decreased, suggesting that the wall assemblies were drying out.

The multilayer sandwich panel had roughly 4.6% better thermal performance than the gypsum drywall case. It exhibited lower annual heat flow, especially at the interior surface, than the reference wall assembly under two scenarios due to the lower thermal conductivity of cementitious panels and kraft-paper honeycomb. Furthermore, compared to the reference wall, the multilayer sandwich panel with a lower U-value had a lower annual heating energy load for the same surface area of both wall assemblies. Therefore, the multilayer sandwich panel is more energy-efficient than the reference wall over the calculation period. Overall, the multilayer sandwich panel with improved thermal performance combined with better environmental impact and lower cost can be considered an alternative to the reference wall with gypsum drywall.

Limitations and Future Research

Future research is needed to understand better the long-term hygrothermal performance of kraft paper honeycomb sandwich panels used as interior wall panels. The study's limitations indicate the need for additional work and investigation: The WUFI database is used to drive the gypsum-based drywall's material properties. As a result, future research should include additional experimental testing of gypsum-based drywall characteristics to provide comprehensive modeling results. Also, more numerical analysis is needed to evaluate different wall assembly design configurations using the developed sandwich panel with additional indoor and outdoor boundary conditions.

Acknowledgment

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