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The hygrothermal performance of continuous and cavity wood fiber insulation

Emishaw Iffa
Mikael Salonvaara
Mengjia Tang
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Buildings and Transportation Science Division

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Emishaw Iffa
Mikael Salonvaara
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OAK RIDGE NATIONAL LABORATORY
Oak Ridge, TN 37831
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ABSTRACT

Wood fiber insulation is an emerging material known for its effective thermal performance and moisture management properties, making it a compelling alternative to conventional insulation. Its vapor permeability and ability to regulate indoor humidity contribute to improved building durability and comfort, particularly in varying climate conditions. The goal of this project is to characterize the hygrothermal performance of a new wood fiber insulation product line in U.S. climate zones and to facilitate the design and construction of the product in residential and light commercial building envelopes. This study investigates the thermal and hygrothermal performance of wood fiber insulation, both as continuous and cavity insulation. The research employs an exhaustive simulation task and an environmental chamber test of a wood fiber insulation. Over 400 simulations were conducted to study the hygrothermal characteristics of bio-based wood fiber insulation in various building envelope configurations across four climate zones. Environmental chamber tests were conducted under controlled winter conditions representative of Climate Zone 5A (Chicago, IL) to complement the simulation results. The chamber tests focused on the hygrothermal performance of the wood fiber insulation and the sheathing board to assess the insulation's ability to manage moisture in a cold climate. Simulation and environmental chamber test results were analyzed to evaluate the insulation's consistency and efficacy across diverse climatic zones. Results show that with a proper moisture control strategy, both cavity and continuous wood fiber insulation can work properly in both new and retrofit constructions.

1. PURPOSE AND BACKGROUND

In 2023, GO Lab, Inc. will begin producing three wood fiber insulation product lines at a former paper mill in Madison, Maine. Branded TimberHP, the loose fill, batt, and board insulations will provide the residential and light-commercial construction sectors with high-performance, safe, cost-competitive insulation options that are fully recyclable. Though dry-process wood fiber insulation has been produced in Europe for over two decades and will account for $1 billion in sales in the EU in 2023, the product is not currently produced in North America and is only imported and used on a handful of jobs across the United States and Canada. The goal of this project is to characterize the hygrothermal (moisture and thermal) performance of the product across US climate zones to facilitate design and construction in residential and light commercial building envelopes.

European testing and experience show wood fiber insulation to be an effective thermal and vapor open component of wood framed assemblies, but little test data exist to account for hygrothermal performance of wood fiber insulation used in code-compliant assemblies across the broader climate zones of the United States and Canada. While some similarities exist to other thermal insulations currently available to the domestic market, the hygrothermal performance of wood fiber insulation is also quite unique. Wood fiber's high specific heat capacity and ability to manage moisture, both liquid and vapor, result in performance characteristics not commonly realized when discussing the building envelope in North America.

Some studies have examined its hygrothermal properties compared to other insulation materials. Veitmans et al. (2016) examined the characteristics of wood fiber insulation derived from birch veneer by-products, emphasizing its thermal conductivity and water absorption capacity [2]. They reported that wood fiber insulation exhibited water absorption of 12 kg/m2 per unit thickness and a thermal conductivity of 0.038 W/(m·K). Mounir et al. (2021) employed numerical modeling to study the hygrothermal behavior of wood fiber insulation [3]. The experimental test results of thermal conductivity, heat capacity, and sorption isotherm and desorption isotherms were used as input for the modeling. Their findings indicated an increase in thermal conductivity from 0.045 to 0.06 W/(m·K) for moisture content increasing from 2% to 18%.
Similarly, the volumetric heat capacity increased by 40% for a similar change in moisture content. Slimani et al. (2019) attempted to analyze the behavior of wood fiber insulation subjected to non-isothermal loading under a vapor concentration gradient through modeling and experimentation [4]. Bunkholt et al. (2021)

conducted a comparative study between wood fiber insulation and mineral wool [5]. While both insulation types exhibited similar risks of high moisture levels in walls, wood fiber insulation demonstrated the ability to absorb and distribute moisture over a larger volume, potentially mitigating some moisture-related issues.

This research investigates the hygrothermal effectiveness of wood fiber insulation through hygrothermal modeling, considering various indoor humidity levels and types of construction across different climate zones. Additionally, environmental chamber tests were conducted for retrofit and new construction projects to evaluate the hygrothermal performance of the wood fiber insulation alongside other components employed in constructing the wall system.

2. THERMAL/ HYGROTHERMAL PROPERTY CHARACTERIZATION OF WOOD FIBER INSULATION

The measured material properties, including density, heat capacity, thermal conductivity relative to temperature and relative humidity, water vapor transmission rate, sorption isotherms at a constant temperature and varying relative humidity, and liquid uptake characteristics, of board and loose fill wood fiber insulation loose-fill and board products are evaluated in accordance with ASTM International standards.

2.1 Density

The density measurements adhere to the standards outlined in:

- ASTM C303-21: Standard Test Method for Dimensions and Density of Preformed Block and Board–Type Thermal Insulation [6].
- ASTM C167-18: Standard Test Methods for Thickness and Density of Blanket or Batt Thermal Insulations [7]

The materials are prepared into uniform 0.3048 m (12-inch) square samples for the dimensions of the heat flow meter apparatus. Density is calculated by measuring the size and mass of each material.
The measured density values for the loose0fill and board wood fiber insulation are shown in Table 1.

Table 1. The density of wood fiber insulation.

Wood fiber insulation:	Thickness [mm]	Density [kg/m³]
Board	42	131
Loose-fill	57	78

2.2 Thermal Conductivity

The thermal conductivity of the wood fiber insulation board was assessed following ASTM C518 guidelines, utilizing a Fox 314 Heat Flow Meter (HFM) [8]. Tests were conducted in triplicate on 0.3048 m × 0.3048 m size specimens. The apparatus was configured in auto thickness mode throughout the measurement process to determine the distance between the upper and lower plates accurately. The thermal conductivity test was conducted under different temperatures and relative humidity to study its temperature and moisture dependency.
Before conducting thermal conductivity measurements, the samples were stored under laboratory conditions: at 19°C and relative humidity (RH) of 31%. To explore the impact of temperature on thermal conductivity, three temperature sets were utilized, with the upper and lower plates of the HFM set at -4°C/24°C, 10°C/38°C, and 24°C/52°C, corresponding to mean temperatures of 10°C, 24°C, and 38°C, respectively.
Samples of each material were exposed to specific conditions corresponding to three relative humidity (RH) levels at a mean temperature of 24°C: 0%, 50%, and 80%. These conditions included placement in a 0% RH oven at the standard laboratory temperature of 19°C with dry air circulation and exposure to a climate

chamber set at 24°C with RH levels of 50% and 80%. Following one month of exposure to ensure stable moisture equilibrium, the samples were sealed with polyethylene to maintain their relative humidity levels during subsequent testing. This testing involved using the Heat Flow Meter (HFM), which employs different upper and lower plate temperatures to measure thermal conductivity. Table 2 and 3 show the thermal conductivity of the wood fiber insulation materials as a function of temperature and density, respectively.

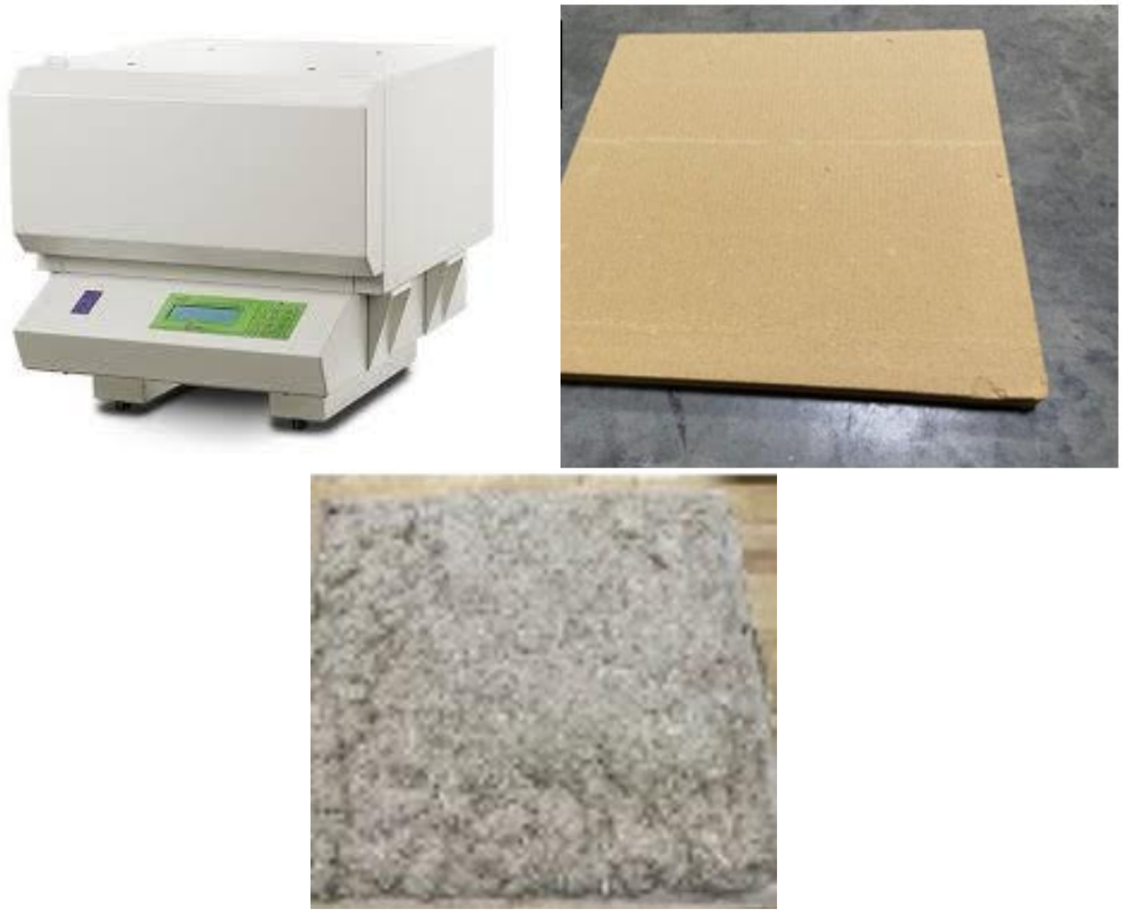


Figure 1. Heat flow meter and test specimen.

Table 2. Measured thermal conductivity at different temperatures.

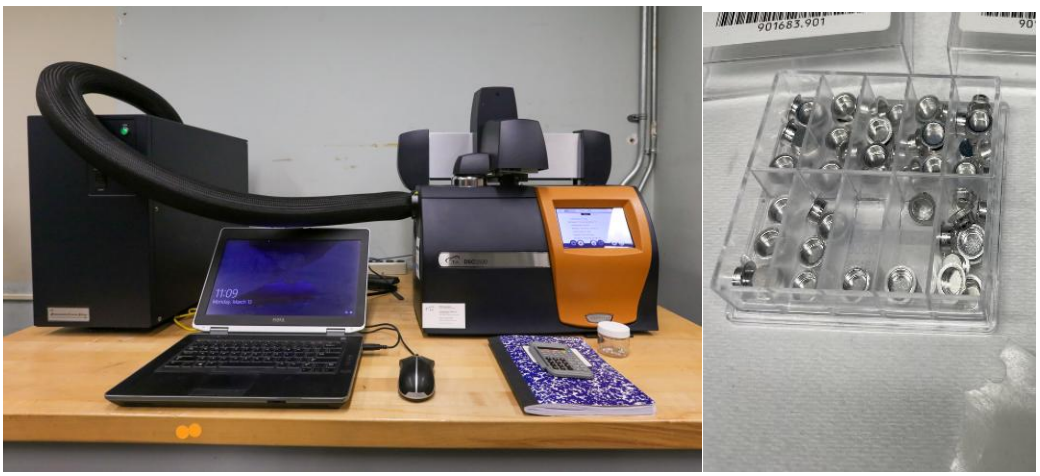
Wood fiber insulation:	Thermal conductivity at different temperatures, [W/(m·K)]		
	10 °C	24 °C	38 °C
Board	0.042	0.042	0.045
Loose-fill	0.046	0.048	0.050

Table 3. Measured thermal conductivity at different relative humidity.

Wood fiber insulation:	Thermal conductivity at 24 °C, [W/(m·K)]		
	0% RH	50% RH	80% RH
Board	0.039	0.042	0.050
Loose-fill	0.042	0.046	0.057

2.3 Heat Capacity Measurement

The heat capacity of the material was measured using a differential scanning calorimeter (DSC) in accordance with ASTM E1269, the Standard Test Method for Determining Specific Heat Capacity by Differential Scanning Calorimetry [9]. To conduct the specific heat capacity measurement, the test specimen was first prepared into a 5 mg portion and sealed in the sample pan, as illustrated in Figure 2. Temperature ranges between 30°C and 50°C were selected for the analysis, with increments of 5°C. Throughout the test, the DSC test chamber was heated at a rate of 20°C/min.



(a) (b)

Figure 2. (a) Differential scanning calorimeter (b) Specimen pan.

Table 4. Heat capacity measurements of wood fiber insulation

Wood fiber insulation:	Heat capacity at different temperatures, [J/(g·°C)]				
	30 °C	35°C	40 °C	45°C	50°C
Board	1.82	1.89	1.99	2.11	2.24
Loose-fill	1.77	1.95	2.19	2.46	2.77

2.4 Sorption Isotherm

Sorption isotherm determines the equilibrium relationship between a material's moisture absorption capacity and surrounding relative humidity.

In this study, instead of employing the conventional method of placing prepared samples in an environmental chamber to measure added moisture content until reaching equilibrium (ASTM C1498-04a), a desiccant jar and aqueous solutions are utilized to acclimate the surrounding relative humidity of the wood fiber insulation specimen, following ASTM E104-2a standards [10, 11] (Figure 3a). Three salt solutions (magnesium chloride, sodium chloride, and potassium nitrate) dissolved in distilled water achieve targeted equilibrium relative humidity levels ($MgCl_2$=32.8%, NaCl=75.3%, and KNO_3=93.6%), as detailed in Table 5. Temperature/relative humidity data loggers (HOBO) validate the attainment of the target equilibrium relative humidity. Triplicates of wood fiber insulation board materials, sized nearly 20 g, are prepared and placed in a drying oven at 100°C (Figure 3b).

In preparation for testing the sorption isotherm at 100% relative humidity (RH), the wood fiber insulation was cut into pieces measuring 51 mm × 51 mm, subjected to drying in an oven at 100 °C, and then weighed to determine the dry mass. Subsequently, each specimen, consisting of a single piece of wood fiber insulation weighing 18g, was immersed in distilled water.

The procedure involves weighing the cups containing the specimens before placing them in the desiccant jars, repeated until the daily weighing difference relative to the previous day is within 0.1% for three successive days. Figure 4 shows the sorption isotherm graph of both board and loose-fill based wood fiber insulation.

Table 5. Saturated aqueous salt solutions and their corresponding equilibrium relative humidity

Salt solution	RH
$MgCl_2$	32.8%
NaCl	75.3%
KNO_3	93.6%

(a)

(b)

Figure 3. (a) Wood fiber insulation prepared specimen and a desiccant jar with acclimated RH and temperature using salt solutions (b) Drying ovens.

Table 6. The average of equilibrium moisture content (weight %) at 32.9%, 75.3%, 93.8%, and 100% RH.

Wood fiber Insulation	32.9% RH	75.3% RH	93.8% RH	100% RH
Board	2.75	9.95	18.3	842
Loose-fill	3.96	12.0	22.4	1.39e3

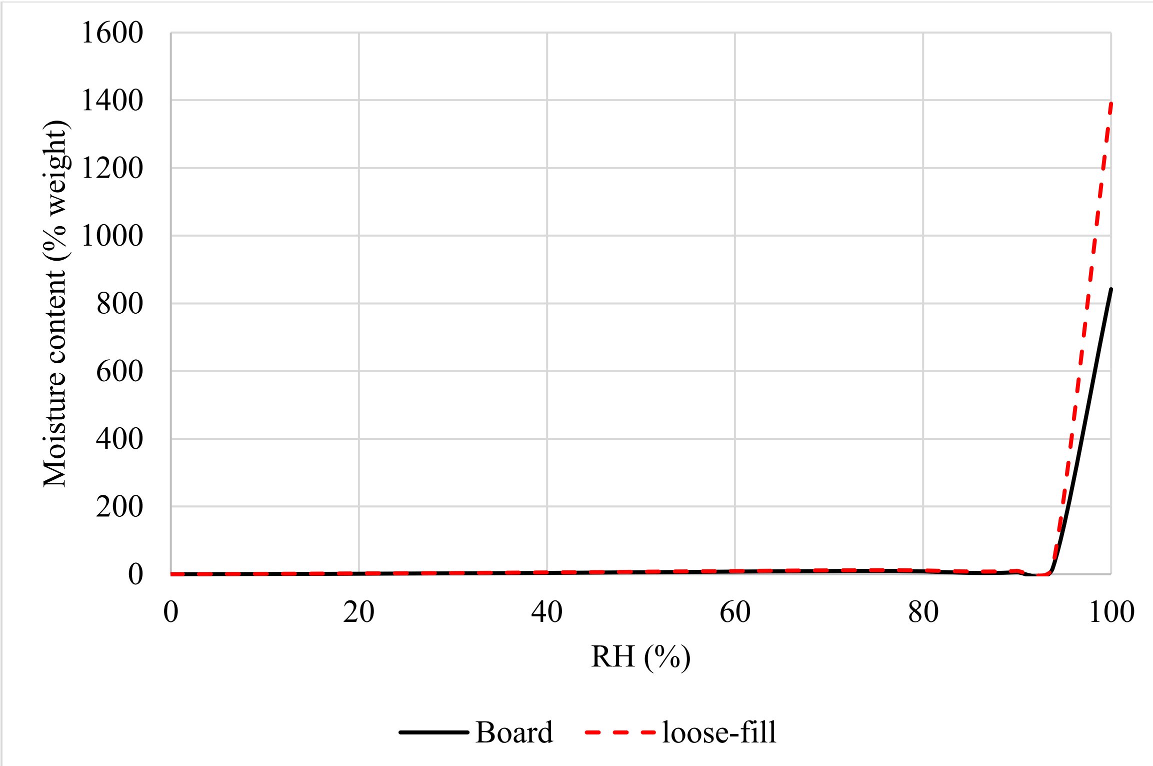


Figure 4. Sorption Isotherm of a wood fiber insulation.

2.5 Water Vapor Transmission (Vapor Permeance)

Water vapor transmission rate (WVTR) quantifies the amount of water vapor that passes through a material per unit time and unit area. A water vapor transmission test provides a vapor permeance of a specific sample. Vapor permeance is the capacity of a material to allow water vapor to pass through it.
The ASTM standard utilized for the water vapor transmission rate (WVTR) test is ASTM E96 [12], which employs both the desiccant and water methods to assess permeabilities under various relative humidity (RH) levels. A calcium chloride desiccant is employed for the dry cup method (0% RH), while the wet cup method utilizes saturated salt solutions: magnesium chloride, sodium chloride, and potassium nitrate.

To achieve different RH levels for each material, samples with different RH cups are placed in two climate chambers (Figure 4), one at 24°C and 50% RH and the other at 24°C and 80% RH, as shown in Table 7. The wood fiber insulation is prepared in circular samples with a diameter of 0.1524m, and salt solutions are added to the cups, which are then wax-sealed (Figure 6).

Permeability calculations are conducted following ASTM E96 procedure. Samples are stored in the climate chambers, and daily measurements of each sample's mass are taken until equilibrium is reached. The permeance for each material is then determined based on these measurements.

Table 7. Average relative humidity levels for water vapor transmission measurements.

RH in the test cup	RH in the chamber	Average RH

0	50	25
33.1	50	41.6
75	50	62.5
94.6	50	72.3
94.6	80	87.3

Figure 5. Environmental chamber and test samples inside the climate chamber.

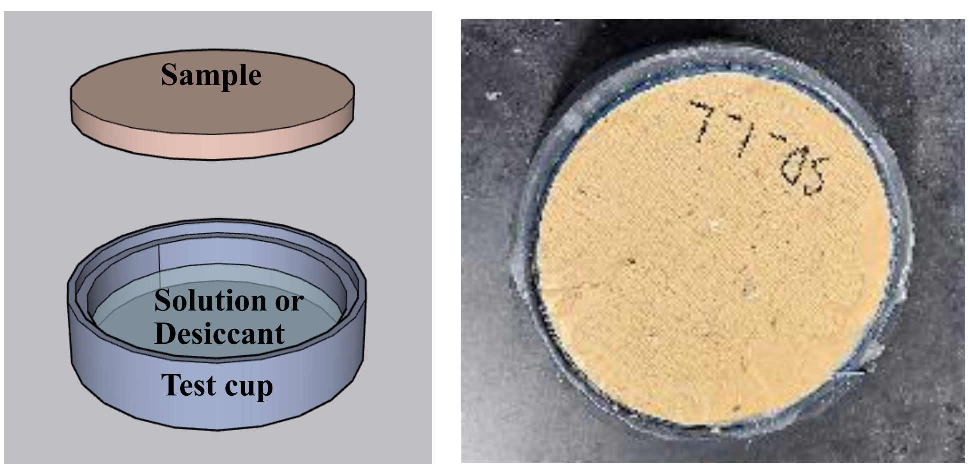


Figure 6. Test cup with the aqueous solution and waxed samples.

Table 8. Measured water vapor permeability at different relative humidity levels.

Wood fiber insulation:	Thickness [mm]	Water vapor permeability [ng/(Pa·s·m)]				
		25% RH	41% RH	63% RH	72% RH	87% RH
Board	19	36.4	137	109	100	204

3. SIMULATION AND EXPERIMENTAL DESIGN

3.1 Simulation Design

A long-term hygrothermal modeling was conducted using WUFI® Pro 6 to analyze the performance of the wood fiber insulation as a cavity insulation in new construction and an exterior continuous insulation board for a retrofit system.

For new construction, the wall components included a cladding (vinyl siding and fiber cement), along with a drainage and ventilation system, varying water-resistant barriers (WRB) with different perm ratings, an Oriented Strand Board (OSB) sheathing, and a cavity insulation (loose and batt WFI). Vapor barrier options ranged from poly and Kraft to none, followed by a gypsum board for a drywall and optional paint coatings with different perm ratings. In retrofit scenarios, the wall system mirrored new construction as shown in Table 9, with variations in cavity insulation in 2×4 wood frame construction: cellulose or no insulation and an additional exterior continuous insulation with 40mm thickness. The Climate Zones 4A (Baltimore, MD), 4C (Seattle, WA), 5A (Chicago, MN), and 6A (Minneapolis, MN) were used for the analysis.

The performance of the wall systems was evaluated based on the maximum moisture content of the sheathing board and mold index of the exterior sides of the cavity insulation. For retrofit wall construction scenarios, the analysis evaluated the maximum moisture content of the WFI board.

Table 9. Lists of the wall components from exterior to interior and varied parameters.

	Wall component	Wall component type	
		New construction	Retrofit
1	Cladding	Vinyl siding, Fiber cement	
2	Air cavity	Drainage and vented	
2b	Continuous insulation	N/A	WFI board (80 mm)
3	WRB	5 perms [286 ng·s/(m^2·Pa)], 50 perms [0.003 mg·s/(m2·Pa)],	
4	Sheathing board	OSB	
5	Cavity insulation	WFI-loose fill & -batt	Cellulose, None
6	Vapor Barrier	Poly, Kraft, None	
7	Drywall	Gypsum board	
8	Paint	8 perms [458ng·s/(m^2·Pa)], None	

3.2 Experimental Design

The experimental study employed two construction types: a retrofit configuration and a new wall frame construction. The new wall construction consisted of loose-fill wood fiber insulation in a 2×6 wood frame wall, a fiber cement siding, an OSB sheathing board without a vapor barrier, a water-resistive barrier, and a painted gypsum drywall. In contrast, the retrofit construction utilized a 2×4 wood frame wall with a cellulose cavity insulation, an OSB, an 80mm thick wood fiber insulation board, also finished with a painted gypsum drywall.

In the new construction, two capacitance-type relative humidity (RH) sensors were placed on the sheathing board and the interior side of the drywall, along with two thermocouples on the exterior side of the fiber cement and the indoor side of the drywall. For the retrofit configuration, as shown in Figure 7, three RH sensors were positioned on the exterior side of the wood fiber insulation, the sheathing board, and the interior side of the drywall. Additionally, three thermocouples were installed on the exterior side of the fiber cement, the sheathing board, and the indoor side of the drywall. Figure 8 shows images of the constructed wall systems.

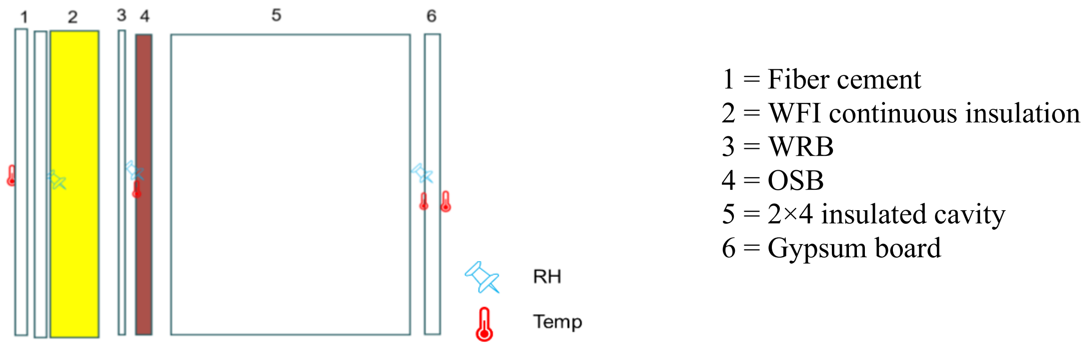


Figure 7. The retrofit wall panel layout for a wall without a vapor barrier.

The environmental chamber simulated Climate Zone 5A, emulating Chicago's cold winter climate, to replicate outdoor weather conditions. Over two months, the test was conducted with specific parameters set for both indoor and outdoor environments.

The outdoor temperature and relative humidity were varied in a diurnal cycle following the winter conditions representative of Climate Zone 5A (Chicago, IL). The average outdoor temperature was 23°F, while the average outdoor relative humidity was 75% RH. The indoor temperature and relative humidity were maintained at 68°F and 40% RH, respectively. Figure 9 illustrates the corresponding indoor and outdoor temperature and relative humidity values used throughout the test.

(a) (b) (c) (d)

Figure 8. Constructed wall system: (a) Fiber cement cladding, (b) WFI board, (c) Loose-fill WFI, and (d) painted drywall.

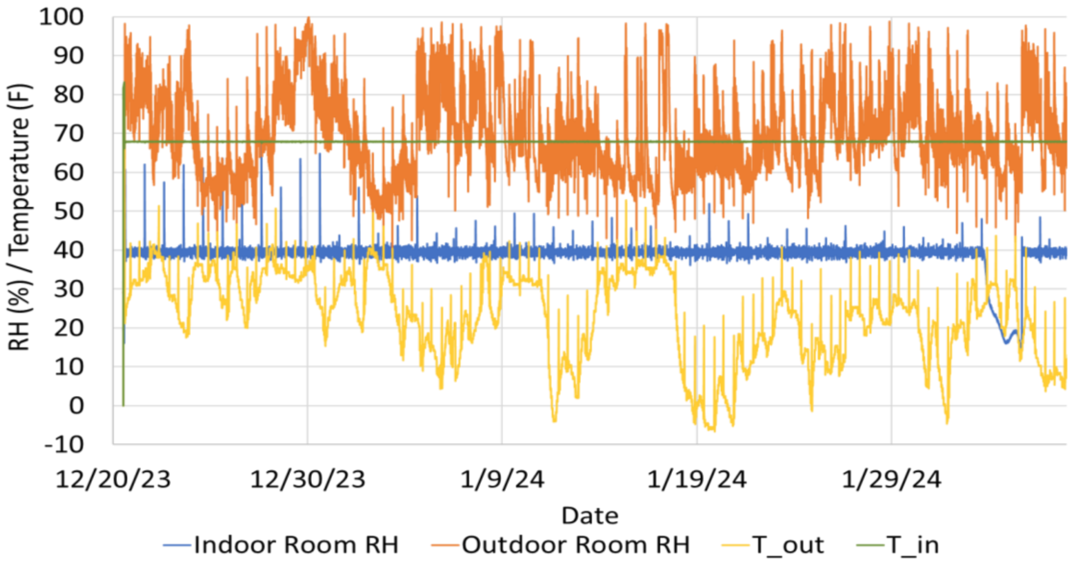


Figure 9. The indoor and outdoor temperature and relative humidity during the test.

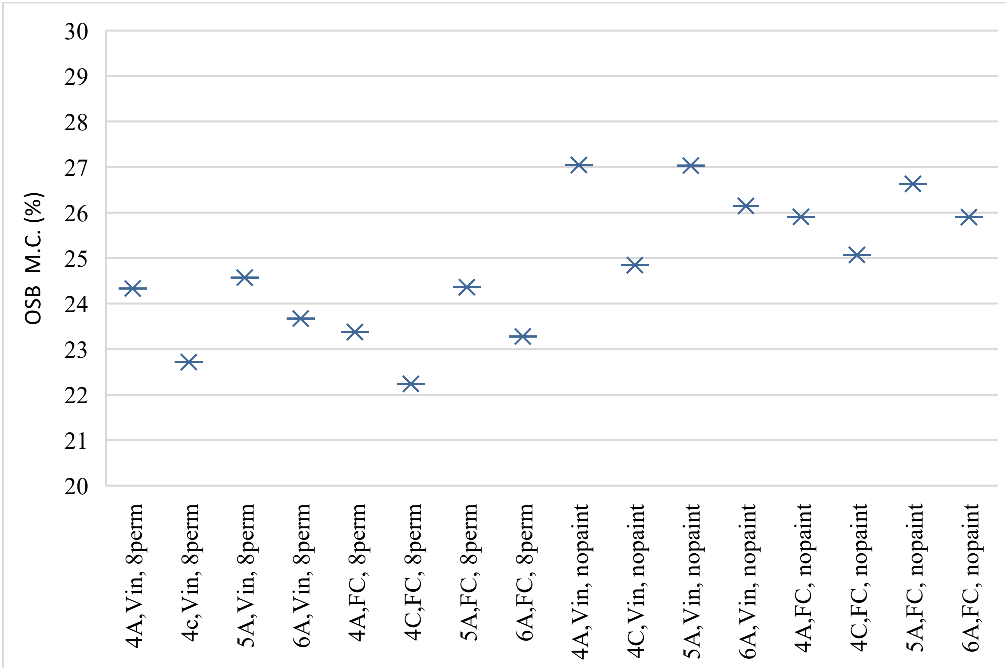
4. RESULTS AND DISCUSSIONS

This section delves into the simulation results of wood frame wall systems, examining their performance when used as the cavity insulation in new construction scenarios and as the continuous board insulation for retrofit construction. It explores four different climate zones, considers two types of indoor humidity, and analyzes various configurations of wall systems for both new and retrofit construction projects. The environmental chamber test evaluates the hygrothermal performance of wood fiber insulation over two months, replicating the winter weather conditions of Climate Zone 5.

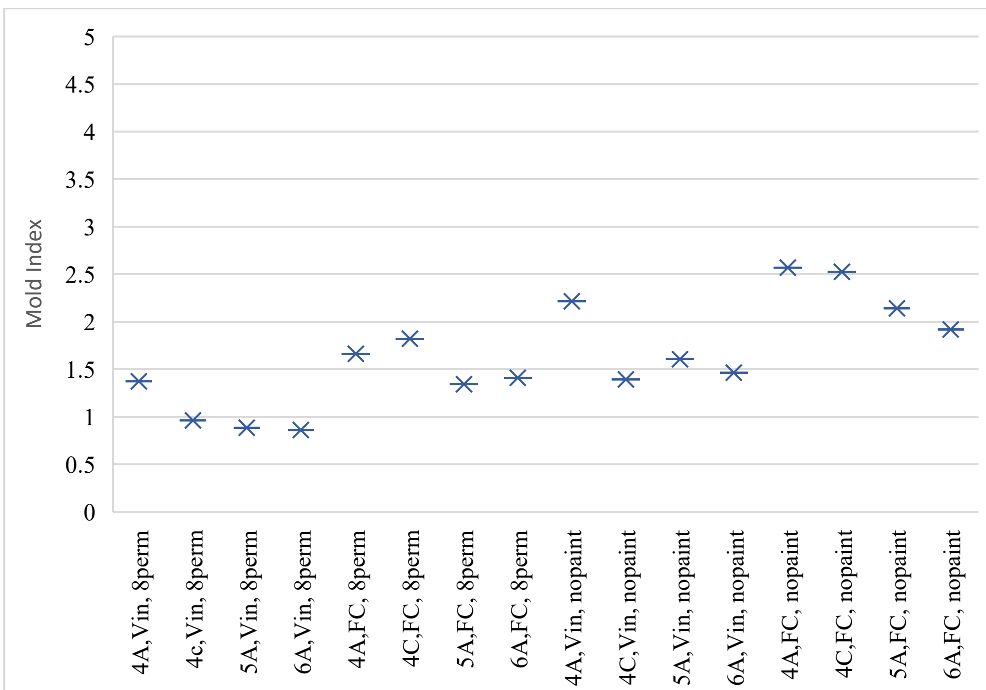
4.1 Simulation Results

About 200 simulations were conducted using a simulation matrix encompassing four distinct climate zones (4A, 4C, 5A, and 6A), two indoor humidity levels (high [40% to 70%] and normal [30% to 60%] in accordance with EN15026), and two types of claddings (absorptive and non-absorptive). Additionally, variations included two types of cavity insulation (loose-fill and batt WFI) and three types of vapor barriers (none, kraft with 5 perms, and poly with 0.5 perms) were considered. Drywall options included unpainted and painted with an 8-perm rating, water-resistant barrier was modeled with a permeance of at 5 perms, and OSB was used as a sheathing board. The performance monitoring criteria for the wall assemblies deemed a mold index of 3 or higher and a sheathing board moisture content exceeding 20% as indicative of failure.

Across all simulation scenarios, the mold index for the exterior sides of the cavity insulation consistently remained below 3. In most cases, the moisture content of the OSB remained under the threshold of 20%. Instances where the moisture content exceeded 20% were observed in wall constructions with combinations of high indoor humidity, absence of a vapor barrier, and a loose-fill cavity insulation, as shown in Figure 10 (a). Wall assemblies featuring the batt insulation exhibited lower sheathing board moisture content compared to those with loose-fill insulation. Furthermore, both class I (Polyethylene) and class II (Kraft) vapor retarders effectively maintained the moisture content of the OSB below 20%, demonstrating their efficacy in moisture management. Similarly, the mold index remained below 2.5 except climate zones of 4A and 4C with no vapor retarder, paint and fiber cement (absorptive cladding) as shown in Figure 10 (b).



(a)



(b)

Figure 10. (a) The new construction moisture content (M.C.) of the OSB (b) The Mold Index of the new construction. Key: Four climate zones (4A, 4C, 5A and 5C), vinyl (V) and fiber cement (FC) sidings and painted (P) and unpainted (NP) drywall.

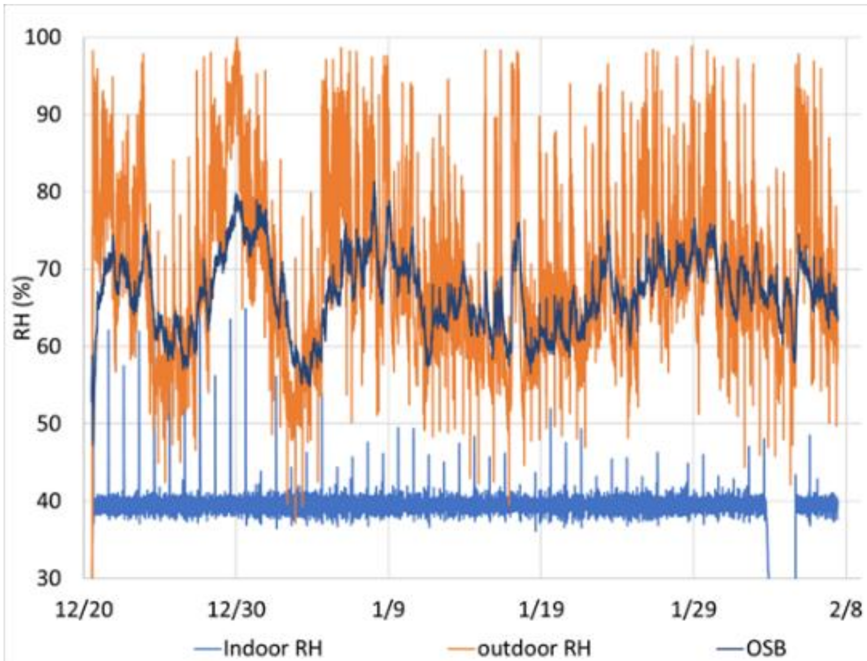
In the retrofit scenario, as depicted in Figure 7, the retrofit system comprised a 40 mm thick wood fiber insulation and a 2×4 cavity filled with a cellulose insulation, mirroring existing cavity insulation conditions. A simulation matrix and failure criteria similar to those employed in the new construction study were employed. Wall systems encountering high indoor humidity levels, as stated above, and lacking a vapor barrier exhibited OSB moisture content surpassing 20%. The absence of drywall paint in cases with high indoor humidity levels and no vapor barrier has shown the mold index of the exterior side of the cavity insulation to be more than 3. Table 9 illustrates the moisture content and mold index for the wall systems exceeding the designated criteria.

Table 9. Retrofit wall systems with high indoor humidity, no vapor barrier, and unpainted drywall.

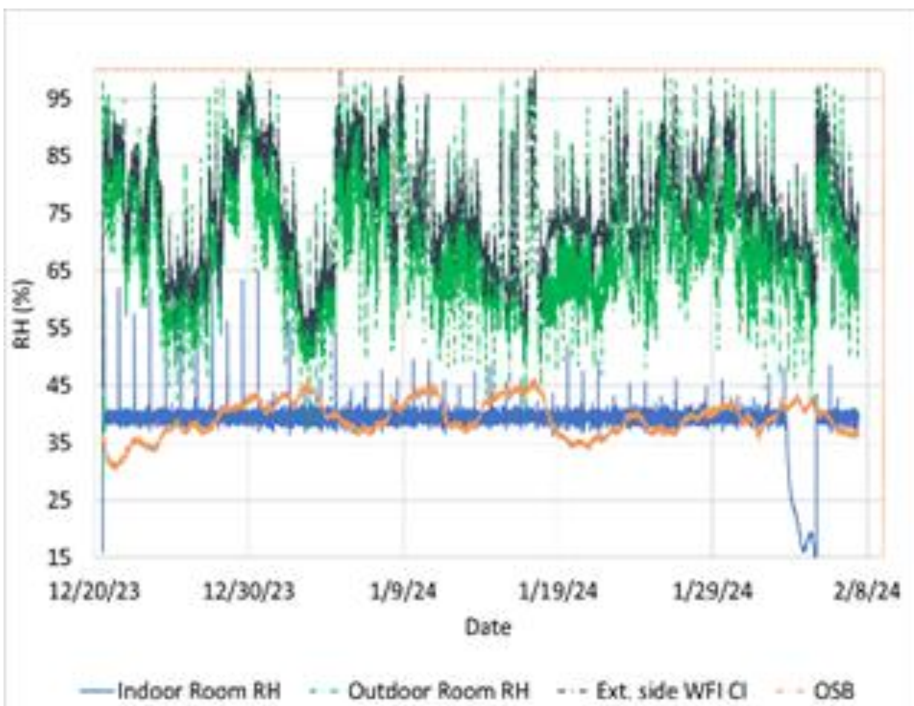
CZ, Cladding	Mold index	MC OSB (%)
5A, Vinyl siding	4.86	36.02
6A, Vinyl siding	4.99	37.65
4A, Fiber cement	4.72	31.89
4C, Fiber cement	3.49	23.18
5A, Fiber cement	4.82	33.86
6A, Fiber cement	4.94	34.78

4.2 Environmental chamber test

Utilizing the environmental chamber test, the new construction and retrofit wall systems underwent a two-month examination under climate Zone 5A conditions. Figure 11(a) illustrates that the relative humidity measurements within the OSB consistently remained below 80% throughout the test duration, indicating that the wall system featuring the loose-fill cavity insulation can perform without moisture-related issues. Figure 11 (b) depicts the relative humidity values of both the sheathing board and the continuous wood fiber insulation (WFI) board. The relative humidity of the OSB remained near the dry indoor humidity level throughout the entire testing period, highlighting its compatibility and efficacy in managing moisture within the building envelope. Additionally, the exterior relative humidity of the WFI closely mirrored the relative humidity profile of the absorptive cladding (fiber cement) utilized in the wall assembly.



(a)



(b)

Figure 11. RH values of OSB and WFI for (a) new and (b) retrofit construction.

5. CONCLUSION

The study investigates the hygrothermal performance of the wood fiber insulation utilized as the cavity and continuous insulation through environmental chamber testing and simulation analysis. The simulation findings highlighted the effectiveness of WFI when coupled with appropriate moisture control strategies, such as water-resistant barriers, drainage, ventilation, and vapor barriers, across all simulated climate zones. Furthermore, the environmental chamber tests demonstrated that the moisture content of the OSB remained below the critical relative humidity threshold of 80% in both continuous and cavity insulation configurations. In scenarios involving absorptive claddings, the exterior side of the continuous WFI exhibits a comparable relative humidity level to that of the cladding.

ACKNOWLEDGMENTS

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