Behavior of Wall Assemblies with Different Wood Sheathings Wetted by Simulated Rain Penetration

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ABSTRACT

Field observations over the last two decades have shown that water infiltration through building envelope defects and into wall assemblies can cause serious damage if water accumulates within the core of the wall. If at high moisture content and appropriate temperature for sufficient time, wall components such as wood framing or wood-based sheathing are vulnerable to mold growth and biodegradation.

Several hygrothermal studies have looked at large amounts of water introduced in wall assemblies. The objective of the present study was to investigate the capacity of a wall assembly to manage small amounts of water penetration. The work performed is experimental and includes 19 specimens, grouped into a testing hut within a large environmental chamber, subjected to a series of three tests. The behavior of three specimens during two of these tests is discussed. The paper presents the experimental protocol including the test specimen design, the monitoring instrumentation, the two wetting methodologies used, and the environmental conditions to which the walls are subjected during the wetting and drying phases of the experiment. One wetting method consists of injecting water according to a measured leakage rate in an actual window/wall failure and actual rain frequency and duration extracted from a 20-year database of Montreal weather. The second method involves uniformly wetting a framing component by initial partial immersion. The results presented illustrate the role of different wood-based sheathings in the wetting and drying behavior of the wall assemblies. The sheathing materials include oriented strand board, plywood, and asphalt-coated fiberboard. Moisture content and relative humidity measurements for series of identical specimens built with different sheathing panels are presented during wetting and drying modes. The rate of drying is compared and the role of temperature gradient is demonstrated.

INTRODUCTION

Two experimental wetting setups have been carried out on 19 large-scale wood-frame wall assemblies constructed with different types of wood-based sheathings with the intent to evaluate their hygrothermal performance when exposed to simulated rain penetration. In the first wetting method, water is dripped into the wall specimen at the top center of the stud cavity according to a rate determined from statistical weather analysis, application of CFD-calculated wind-driven rain catch ratios, and water leakage tests through an actual window/wall failure. In the second setup, a wood component of each wall assembly is initially wetted by partial immersion and then inserted into the assembly, where its drying is monitored. The experimental protocol for the tests is presented and some results of the behavior of six of the wall specimens are presented. More results will be analyzed and published at a later date.

CONTEXT

Field observations over the last two decades have shown that water infiltration through building envelope defects into wall assemblies can cause serious damage if water accumulates within the core of the wall. If at high moisture content and appropriate temperature for sufficient time, wall components

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such as the wood framing or the wood-based sheathing are vulnerable to mold growth and biodegradation. This has been experienced in many locations, notably the lower mainland of British Columbia, where the climate, characterized by mild weather and significant rainfall, combined with faulty water management detailing of the envelope, led to numerous cases of water ingress and wood components deterioration (Barrett 1998).

Several experimental studies, including those of Ojanen (1998), Zarr et al. (1995), and Hazleden (2001), have examined the role of sheathing in the hygrothermal performance of wood-frame wall assemblies. Ojanen (1998) performed an experiment including three test wall assemblies with different wood sheathings: plywood, OSB, and porous wood fiberboard. The walls included no framing members and were installed horizontally to facilitate one-dimensional heat and moisture transfer. The moisture source for each assembly was a 10 mm (13/32 in.) pool of water at the bottom of a plastic box in which sat the thermal insulation. Results showed that the wall with the porous wood fiberboard experienced the highest moisture mass flow; next came the plywood, and then the OSB. This ranking was due to the higher vapor permeability of the sheathing. Zarr et al. (1995) performed an experiment of 12 wall assemblies that included two specimens sheathed with fiberboard and plywood exposed to moisture movement by diffusion only. Each wall was equipped with a small, 0.305 m (12 in.) diameter metering area set up to ensure no transverse moisture movement. The specimens consisted of unpainted gypsum board, glass fiber insulation, sheathing, and sugar pine siding. The walls were subjected to a 42-day steady preconditioning period, four winter periods, alternating between steady-state and diurnal outdoor conditions, and a final steady summer period. The moisture content measurements show that the higher vapor permeability of the fiberboard increased the outward moisture flow compared to the plywood panel, slightly reducing the moisture content on the inside surface of the sheathing but also increasing the likelihood of condensation on the interior surface of the siding.

The Envelope Drying Rates Analysis (EDRA) experiment also examined the role of sheathing in the drying of wood-frame assemblies. The project's main objective was to evaluate the comparative drying rates of 12 different wall assemblies and involved a large-scale experiment composed of two successive tests (Hazleden 2001; Hazleden and Morris 2001). Wetting of the wall panels was performed by placing the walls, devoid of insulation and interior finish, down in a pool of water for ten days such that the water level was within 6 mm (¼ in.) (test 1) and 18 mm (11/16 in.) (test 2) of the plywood or OSB sheathings with the intention of evenly wetting the stud lumber. Steady-state conditions were applied to the wall specimens during the drying phase of the tests. Results showed that in spite of the plywood-sheathed panels incurring higher moisture contents at the beginning of the drying phase, walls with plywood sheathing dried at a faster rate than comparable panels with OSB. Hypotheses suggested that the differences in moisture performance were not the result of panel design but were rather dependent on the amount of water they had absorbed. However, the Hazleden and Morris (2001) analysis of the total panel moisture absorption and desorption showed that there was no correlation linking the moisture gained to the percentage of moisture lost in either the plywood and OSB wall assemblies.

Another recent study that dealt with the hygrothermal performance of wood-based sheathing is the Moisture Management in Exterior Wall Systems project, or MEWS. The goal of the study was primarily to predict, using the hygIRC heat, air, and moisture numerical model, the hygrothermal performance of wall systems with various types of cladding that had been subjected to wetting due to simulated rainwater infiltration. The boundary conditions, including temperature, relative humidity, horizontal rainfall, wind speed, and solar radiation for various North American climates, were established using hourly weather data for each reference year. The rates of water insertion were determined in a three-step process:

1. determine the moisture load imposed by a given climate using weather data,
2. determine the proportion of that load that can reach the face of the wall by utilizing Straube's (2000) simplified driving rain prediction tool, and
3. for each cladding system, characterize the water loading directly into the stud cavity as a function of air pressure differential due to a given water leakage path at a through-the-wall penetration by performing water penetration tests using IRC's Dynamic Test Wall Facility.

The MEWS project included several parametric analyses to examine the role of various material properties on the drying response of the various types of walls. Of interest are analyses comparing the roles of OSB, plywood, and uncoated fiberboard in two different climates, Wilmington, North Carolina, and Ottawa, Ontario. The modeling analyses concluded that changing the type of wood sheathing has a "zero to small" effect on the overall moisture performance on all but the masonry-clad wall assemblies (Beaulieu et al. 2002).

The above studies tend to demonstrate that the permeability of the sheathing influences the drying rate of the assembly. However, the limitations of the studies must be taken into account. For example, in many cases, the experimental environmental conditions created do not represent the cyclic temperature and relative humidity loads to which actual wall assemblies are exposed to in the field. Many test assemblies do not include wood framing members, which, along with the wood sheathing, play a role in the overall moisture absorption/desorption of panels. In some cases, the tests do not replicate three-dimensional heat, air, and moisture transfer that exists in reality with wood-frame assemblies. In addition, wetting loads in most of the experimental work are mainly due to diffusive moisture flow, and those studies that consider water as a moisture source do not reflect field wetting conditions. Considering the limitations of previous studies, additional field and laboratory research is required to establish the behavior of different wall sheathings in terms of type of wall assembly, moisture loading, and type of climate for design purposes.

OBJECTIVES

Two test protocols were carried out to study the hygrothermal behavior of wood-frame wall assemblies subjected to simulated rain infiltration. The overall objectives of the study include:

1. To determine the amount of moisture accumulated and the moisture distribution pattern in each assembly during the wetting phase.
2. To establish the locations within the wood-frame wall panels most susceptible to moisture accumulation for the given water penetration pattern.
3. To ascertain the duration of exposure of various wood components within each test panel to moisture content and temperature conditions that may lead to mold and fungal growth.
4. To determine the drying rate of components at various locations within the assemblies.
5. To evaluate the impact of several parameters on the hygrothermal behavior (points 1 to 4 above) such as: type of sheathing, type of vapor retarder, size of stud, and presence of foam insulation on the exterior side of the assembly.

Two experiments are reported here. The first lasted nine weeks and included a four-week wetting phase followed by a five-week drying phase. The drying phase was composed of two sections, one of four weeks of April and one additional week of May conditions in Montreal. The second test was started with pre-wet components that were then exposed to five weeks of drying in two sections similar to those in the first test. Both tests were preceded by three-week preconditioning phases. The testing facility and the experimental procedure are presented next, followed by some experimental moisture content results from three wood-frame wall specimens built with different wood sheathings.

THE TESTING FACILITY

For this experiment, the Environmental Chamber at the Building Envelope Performance Laboratory was used in the climate chamber mode where the hot and cold boxes were joined to form a 7.5 m (24.6 ft) high by 4.4 m (14.4 ft) wide by 10.5 m (34.4 ft) deep climate chamber, in which temperatures ranging from –40°C to 50°C (–40°F to 122°F) can be maintained and relative humidities ranging from 40% to 75% can be generated (Fazio et al. 1997). The mechanical equipment include a 5-ton screw compressor, a 12000 cfm recirculation fan, and a 25 kW (85300 Btu/h) reheating heater. The walls of the chamber are made of 150 mm foamed polyurethane boards, laminated between 0.8 mm (1/32 in.) aluminum sheets outside and 0.8 mm (1/32 in.) stainless steel sheets inside.

The facility is equipped with a data acquisition system that automatically reads and logs data at a specified time interval—five minutes in this instance. The data acquisition system, as set up for this project, has the capacity for 400 channels including 320 for thermocouples, 24 for relative humidity, and 52 channels that are doubled through electronically switched mechanical relays to measure up to 104 electronic resistance moisture contents and a number of general purpose channels. The custom data acquisition system also has the capability to apply specified calibration factors and given correction factors. Thermocouple calibration was done on a systematic basis rather than on individual sensors. The temperature both inside and outside the test hut was maintained constant using the HVAC system and additional fans and then, after a stabilization period, monitored for one hour and averaged. The averaged temperature reading from each thermocouple was compared to that of a "true" reading from an RTD probe. The RTD probe, calibrated to an accuracy of ±0.2°C, was placed in the center of the test hut. The difference between each thermocouple reading, T_{TC}, and the RTD reading, T_{RTD}, was obtained and used as a correction factor for each thermocouple. Calibration of each capacitive-type relative humidity sensor was performed by using a chilled mirror dew-point hygrometer. A relative humidity simulation chamber, which was controlled by a chilled mirror hygrometer and RTD, was alternatively set to two relative humidities, 40% and 80%, and the zero and the span of the relative humidity sensor's potentiometers were adjusted until the desired accuracy of ±2% was reached. Then the setpoint of the relative humidity simulator was set to 40% relative humidity and ramped up to 90% at 10% intervals to evaluate the deviation between the relative humidity sensor readings and that of the dew-point hygrometer. The calibration curve for the electronic moisture content measurements is based on conditioning several wood or wood-based sheathing specimens at various relative humidities and temperatures until equilibrium moisture content was reached and then taking voltage readings across two moisture content probes installed in each sample.

THE EXPERIMENTAL PROCEDURE

Wall Construction

The first and second tests included 19 and 6 monitored wall specimens, respectively. The test assemblies were designed to reproduce current construction practices. Each wall specimen was 840 mm (33 in.) wide by 1075 mm (42.4 in.) high. This height was chosen to represent that of a wall below a leaky window. Every monitored test assembly was built with two 38 mm × 140 mm (nominal 2 in. × 6 in.) wood studs spaced at 400 mm (16 in.) on center, plus another stud at 200 mm (8 in.) on each side. The resulting side spaces served

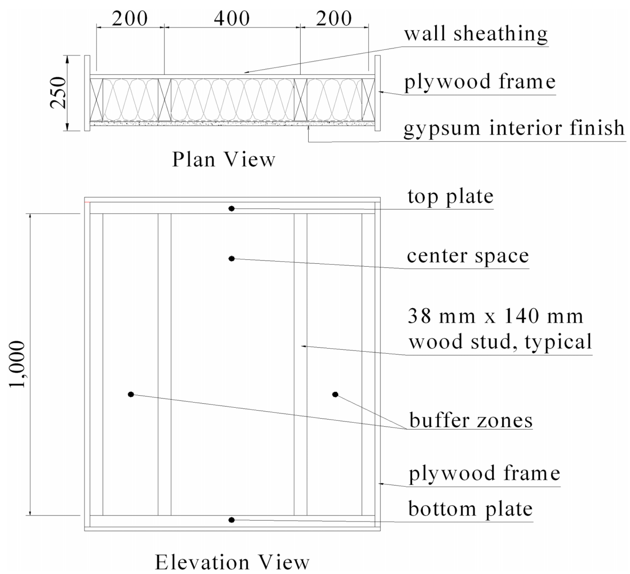

Figure 1 *Schematic elevation of a typical test panel.*

Figure 2 *Photo of installed wall panels within the test hut. The access panels in the gypsum board to reach the gravimetric samples can be seen.*

as buffer zones between the test panel and the adjacent ones, and monitoring was only performed in the central stud space.

The test assembly setup aimed to recreate actual site construction methods. In platform construction methods, the wall framing is nailed into the subfloor wood panel. In a similar fashion, the test specimens were framed on all sides by 16 mm (5/8 in.) thick plywood, as shown in Figure 1. However, the sides and the top plywood did not reproduce actual conditions but provided a frame for the specimen. A modified bituminous membrane was installed on the outside of the plywood framing. The plywood and bituminous membrane minimized moisture and air transport between adjacent test panels. Each assembly was constructed as follows, from inside to outside:

- 13 mm (1/2 in.) gypsum board painted with one coat of primer and two coats of latex paint
- 6 mil (0.15 mm) polyethylene membrane
- stud cavity filled with 140 mm (6 in.) glass fiber insulation
- 38 mm × 140 mm (nominal 2 in. × 6 in.) wood studs at 400 mm (16 in.) center to center
- exterior sheathing
- spun-bonded polyolefin membrane, stapled

The test walls were built independently and then installed into the test hut. The walls were assembled to ensure that the stud members were installed at a 90° angle to the top and bottom plate framing members. The construction of the specimens and the installation of sensors took place in tandem. For example, holes for gravimetric samples were drilled into the wood before the framing members were assembled together. Also, installing the electrical resistance moisture probes and thermocouples from the bottom surface of the bottom plate was executed before the plywood separators were added beneath the bottom plate. Grooves were made into the wood framing members to enable the passage and protect the sensor wiring. During the installation of the specimens into the test hut, 19 mm (3/4 in.) by 19 mm (3/4 in.) by 250 mm (10 in.) long spacers were placed between the specimens to create a space between the assemblies, and shims were used to level the specimens. The leveling was critical to ensure that the water introduced at the top of the panel during the wetting phase ran vertically down the inside surface of the sheathing along the centerline of the panel. A photo of the installed wall specimens within the hut is shown in Figure 2.

Wetting Methodology

Test 1. The intent of this wetting method was to reproduce water penetration through a defect—therefore, a point source—at a realistic dripping rate. An approach for the simulation of wind-driven rain penetration in building envelope testing wetting methodology was developed. The methodology had three steps:

1. To characterize wind-driven rain in terms of average rate of rainfall, determine the wind speed frequencies for every month for the Montreal region. This was done by analyzing a 20-year hourly weather database for Montreal at Dorval airport.
2. To calculate the wind-driven rain on a building façade, determine the catch ratio, i.e., the proportion of wind-driven rain impinging on a building façade to that falling on a horizontal plane. This step was based on the results of a computational fluid dynamics-based work by Blocken and

Figure 3 *Photo of the peristaltic pump used to deliver water to the panels.*

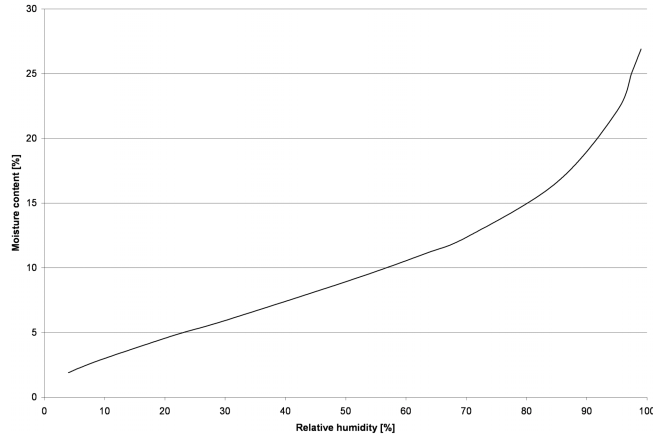

Figure 4 *Adsorption curve for white spruce at 21°C (Hedlin 1967).*

Carmeliet (2001) for a one-story building and the climatic data analysis described in step 1.

3. To determine the fraction of water that penetrates through an intentional windowsill deficiency by conducting a water leakage test based on ASTM E331-00 (ASTM 2000). Leakage tests were performed for four different defect geometries, and a 5 mm high by 10 mm wide windowsill defect was considered for the calculation.

The wetting protocol determined that, on average in Montreal, August is the month with the highest rainfall, and, hence, calculations for the wetting methodology were conducted using August climatic data. The rate of water penetration was determined from the product of the horizontal rainfall, the catch ratio, and the fraction of water that penetrates the defect. From the calculations it was determined that for test 1, water was to be introduced at a rate of 12 mL/h (0.41 oz/h) for 3.5 hours a day, three days a week for four weeks, for a total of 0.5 L over the four-week period. Details of the development of the wetting methodology can be found in Teasdale-St-Hilaire et al. (2003a, 2003b). Water was introduced using a 24-channel peristaltic pump (see Figure 3), which was previously calibrated for the required flow rate and installed on a platform hung from the center of the test hut ceiling. Water was introduced via tubes at the top center inside surface of the sheathing.

Test 2. The intent of the wetting methodology for the second test was to introduce a moisture amount into the walls that was uniform from wall to wall in order to facilitate analysis of the roles of sheathing and vapor retarder material on the drying of the assemblies, therefore a uniformly wetted component. For the second test, 6 bottom plate inserts of 38 mm × 140 mm × 360 mm (nominal 2 in. × 6 in. × 14 3/16 in.) were weighed and then partially immersed face down into a shallow pool of water 13 mm (1/2 in.) deep. The 13 mm (1/2 in.) diameter and 13 (1/2 in.) mm deep gravimetric samples to be fitted into the wetted side of the bottom plate inserts were also wetted in a similar fashion. On a daily basis, the bottom place inserts and the gravimetric samples were removed from the pool of water, toweled dry and then weighed to determine their water absorption with time. The inserts were immersed for 742 hours (31 days) and the gravimetric samples for 619 hours (26 days). At the end of the wetting, holes for gravimetric samples were immediately drilled into each of the six bottom plate inserts, the prepared gravimetric samples installed into the drilled holes and the inserts placed wet side up into the wall assemblies in the Environmental Chamber. Wetting the six bottom plate inserts in this manner increased their moisture content to 55±2%, a range narrow enough to allow comparison of the drying curves.

Climatic Loading

The objective of the testing methodology was to simulate as closely as possible the actual environmental conditions to which walls are exposed in Montreal. Under the average Montreal climate, diffusion and air leakage wetting occurs from around October until April, while drying takes place from around the end of April to September.

Preconditioning Phase. The wall assemblies were subjected to a preconditioning phase where conditions were set to induce wetting due to winter diffusion. A previous experiment performed at the Environmental Chamber (Desmarais 2000) was used as a basis for the target moisture content within the assemblies. In that experiment, after 66 days of cold conditions, the moisture content in the wood and fiberboard components in the wall assemblies leveled off to approximately 12%, similar to the values found in practice. Making use of Hedlin's (1967) spruce adsorption curve, shown here in Figure 4, the indoor and outdoor temperature and relative humidity conditions of 21°C (70°F) and 60%, respectively, were set in the Environmental Chamber during

Table 1. Indoor and Outdoor Temperature and Relative Humidity Conditions for the Wetting and Drying Phases of the Experiment

Period No.	Duration (days)	Period Simulated From To	Indoor Testing Conditions Temp. [°C] (°F)	Indoor Testing Conditions RH [%]	Outdoor Testing Conditions Sinusoidal Function with: Average Temp. [°C] (°F)	Max. Temp. [°C] (°F)	Min. Temp. [°C] (°F)	RH [%]
Wetting Phase								
1	21-28	- -	21 (70)	50-60	-	-	21 (70) (constant)	50-60
Drying Phase								
2	30	April 1 - 30	21 (70)	40	6.3 (43.3)	10.9 (51.6)	1.6 (34.9)	64
3	as necessary	May 1 - 30	21 (70)	43	13.7 (56.7)	18.7 (65.7)	8.6 (47.5)	63

the three-week preconditioning period preceding each test to induce equilibrium moisture content of the wood components within the walls reflecting moisture content conditions expected after a Montreal winter wetting season. The preconditioning phase increased the moisture content level of the wood components from their initial dry levels of 6% to 8% up to the desired 12%. During the preconditioning phase, the vapor retarder and gypsum board were not yet in place and were only installed at the end of the phase.

Wetting Phase. A wetting phase was conducted in the first test to reproduce a four-week wetting period during which water was introduced into the test assemblies to simulate rain penetration due to an envelope defect. The indoor and outdoor temperatures and relative humidities during this phase were maintained at 21°C (70°F) and 50% to 60%, respectively. Even though the indoor relative humidity was perhaps higher than that found in Montreal homes, while normal for Vancouver conditions, it was set to maintain the moisture that was absorbed in the components during the preconditioning and wetting phases. Setting the same indoor and outdoor temperature and relative humidity conditions prevented the occurrence of a moisture drive across the test assemblies during the wetting phase. From Hedlin's (1967) adsorption curve, it was expected that the equilibrium of the wood would be maintained between 10% and 12%.

Drying Phase. The wetting phase was immediately followed by the drying period. For both tests, no water was introduced into the test panels during the drying phase, as if the envelope defect that allowed rain penetration into the wall assemblies had been repaired. The outdoor temperature profile generated in the Environmental Chamber reflected the monthly average and the daily temperature variations calculated with meteorological data from 1981 to 2001 obtained from Environment Canada for Montreal at the Dorval weather station in terms of monthly patterns and daily quasi-sinusoidal variations in temperature. The outdoor relative humidity was also determined based on actual weather data. However, a daily average relative humidity was calculated for each period by taking the daily average from the hourly data provided by the meteorological station and then calculating the mean over the entire period in question. The indoor and outdoor environmental conditions for both the wetting and drying phases are summarized in Table 1.

Monitoring Plan

Moisture Content. In test 1, electrical resistance moisture probes were used in the studs and bottom plate as well as in the sheathing to measure moisture content. Each moisture content probe consists of a pair of metal pins. The shaft of the pins used for the studs and the bottom plates was insulated such that moisture content was measured only at the tip of the pins. In the studs and the bottom plate, sensors were inserted from the side of the buffer cavity and the bottom of the bottom plate, respectively, such that the tips of the probes were at 6 mm (1/4 in.) from the surface. Because of the limited thickness of the sheathing, smaller pins, 1 mm (0.04 in.) in diameter and 7 mm (0.28 in.) in length, were used for the panel monitoring. These pins were uninsulated, gold plated to prevent oxidation, and installed in the sheathing from the cold side to a depth of approximately 6 mm (1/4 in.) from the interior surface. The electrical resistance moisture content measuring technique required correction for temperature and species of wood. This was done for the spruce-pine-fir framing using the correction tables provided by the moisture content transmitter manufacturer, for fiberboard using the calibration data developed by Desmarais (2000), and for OSB and plywood by an empirical equation from Pfaff and Garrahan (1986) (cited in Straube et al. 2002) using species coefficients for OSB and plywood as reported in Straube et al. (2002) and Onysko et al. (2003). The locations of the moisture probes are shown in Figures 5 and 6.

Gravimetric samples were used in both tests 1 and 2 to determine the moisture content of the wood framing as well as the sheathing. Framing gravimetric samples were 13 mm (1/2 in.) in diameter and 13 mm (1/2 in.) in depth. The gravimetric samples

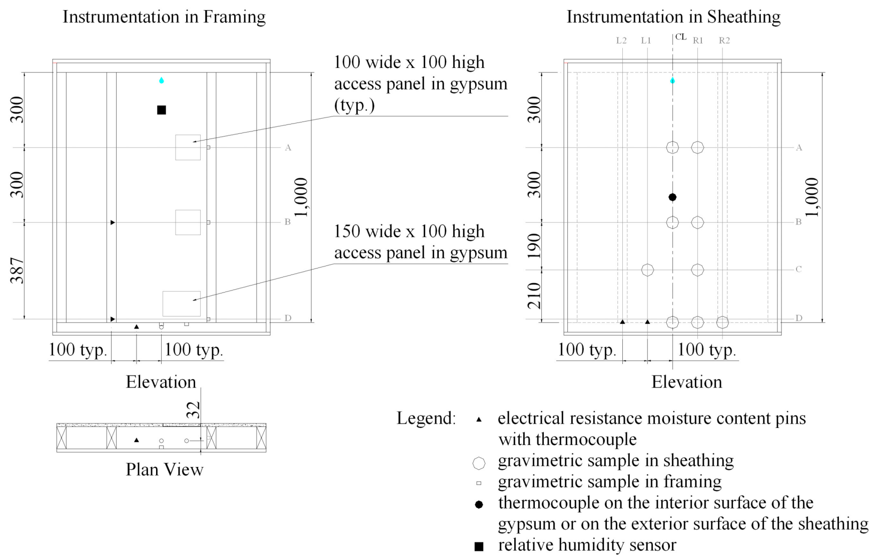

Figure 5 *Elevation and plan views of the moisture content measurement monitoring protocol in the framing and elevation view for the sheathing of the assemblies in test 1. The locations of the electrical resistance moisture pins with their thermocouple, the gravimetric samples in the sheathing and the framing, the thermocouple on the inside surface of the gypsum and outside surface of the sheathing, and the relative humidity sensor are shown.*

that were installed in the top horizontal and vertical sides of the bottom plate were painted with two coats of acrylic paint on the unexposed sides. It was anticipated that water accumulating on the top surface of the bottom plate was likely to pool into the hole in the bottom plate in which sits the gravimetric sample. Thus, the gravimetric samples were partially painted in order to prevent water absorption into the sample from those sides that would not normally be exposed to water if the bottom plate were intact. In test 2, the bottom plate insert in itself served as a large gravimetric sample. The locations of the gravimetric samples as well as the electrical resistance moisture probes are shown in Figures 5 and 6 for test 1 and Figures 8 and 9 for test 2. Figure 7 shows a photo of the gravimetric samples in the sheathing in the bottom row “D” and on the bottom plate vertical surface.

Determination of moisture content by gravimetry is calculated as follows:

$$M(\text{ \% weight}) = \frac{\text{mass of moist sample} - \text{ mass of oven-dry sample}}{\text{mass of oven-dry sample}} \tag{1}$$

The initial moisture content of the small gravimetric samples used in tests 1 and 2 is estimated to have been around 6% to 8%, while that of the larger bottom plate inserts in test 2 was determined to be approximately 16% before wetting.

Temperature. Temperature measurements within the panels were performed with thermocouples, type T, copper and constantan, 30 gauge, with ±0.5°C (0.9°F) accuracy. The thermocouples measured the temperature at locations adjacent to moisture content probes in the wood framing and the exterior sheathings at a depth of 6 mm (1/4 in.), at locations shown in Figures 5, 6, and 8. Thermocouples were also used to monitor the temperature on the surface of the gypsum and of the sheathing in the middle of the each assembly, as shown in Figures 5 and 9. In test 2, thermocouples were also installed at approximately 20 mm (3/4 in.) from each gravimetric sample at mid-depth in order to more closely examine the effect of temperature on drying of the samples.

Relative Humidity. In both tests, the relative humidity within the stud space of the wall specimens was monitored using a capacitance-type relative humidity sensor that has an accuracy of ±4%. For test 1, the relative humidity sensor was placed with its thermocouple at a height of approximately 150 mm (6 in.) from the top of the assembly at mid-point of the insulation, as shown in Figure 5. In the second test, the sensor was moved to the bottom of the cavity at 50 mm (2 in.) from the top wetted surface of the bottom plate insert at mid-span between the gypsum and the sheathing.

Pressure. The pressure difference between the inside and outside of the test hut was monitored with a micromanometer during the wetting and drying phases of the tests.

The results of the wetting and drying performance of the wall assemblies for tests 1 and 2 are presented next.

RESULTS

Test 1

Results of the first three specimens of the 17 specimens wetted and 19 constructed are discussed here. Other results will be processed and published later. These three panels were of identical construction with gypsum board, 140 mm (6 in.) glass fiber insulation, 6 mil polyethylene sheet, and sheathing.

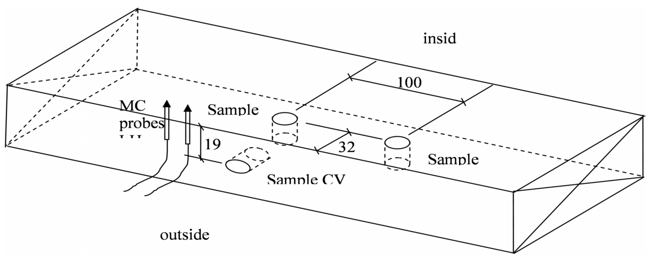

Figure 6 *Isometric schematic of the section of the bottom plate between the studs in test 1. The locations of the gravimetric samples and the electronic resistance moisture content probes are shown. A thermocouple installed adjacent to the moisture content pin pair is not shown for clarity.*

Figure 7 *Photo of the sheathing gravimetric samples and the bottom plate gravimetric sample on the vertical surface.*

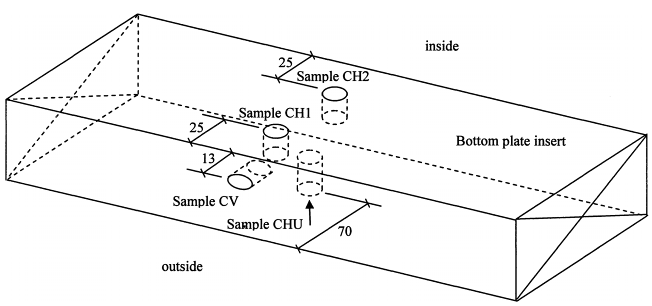

Figure 8 *Isometric schematic of the bottom plate insert for test 2. The locations of the gravimetric samples are shown. Thermocouples are installed adjacent to each gravimetric sample but are not shown for clarity.*

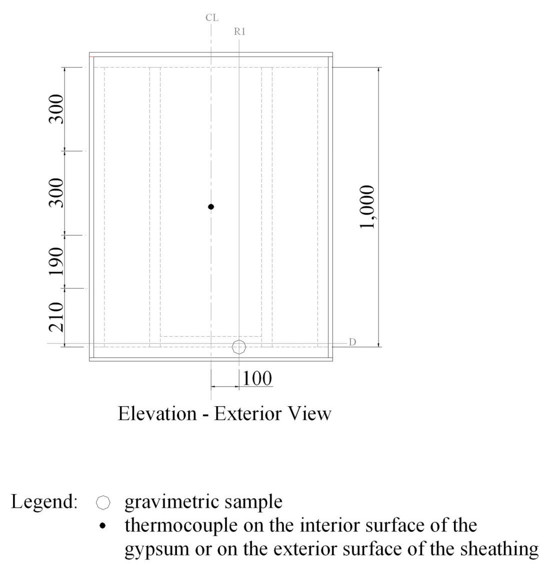

Figure 9 *Elevation and plan views of the monitoring protocol in the sheathing of the wall assemblies in test 2. The locations of the gravimetric sample and of the thermocouple on the outside surface of the sheathing are shown.*

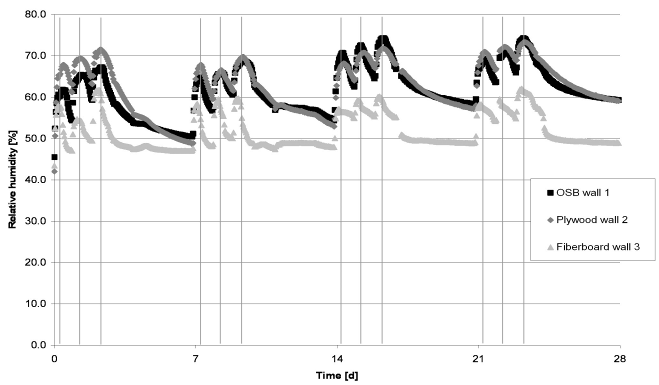

Figure 10 *Relative humidity in the stud cavity at 150 mm (6 in.) from the top in walls 1, 2, and 3 in the wetting phase of test 1.*

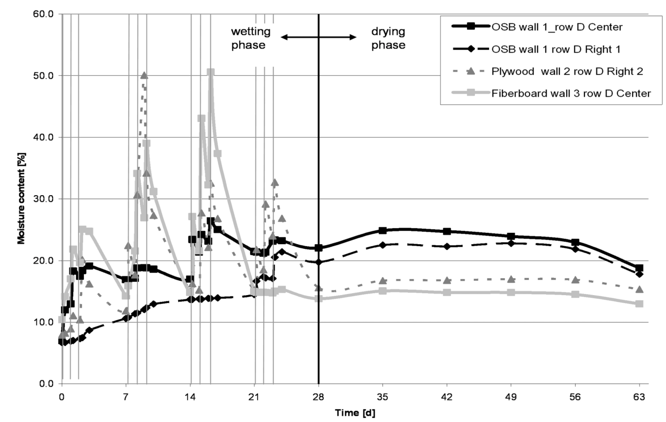

Figure 11 *Moisture content of sheathing gravimetric samples of walls 1 (OSB sheathing), 2 (plywood sheathing), and 3 (asphalt-impregnated fiberboard sheathing) in test 1.*

The sheathing panels were, respectively, for specimen 1, OSB, specimen 2, plywood, and specimen 3, fiberboard.

By the end of the wetting phase, the following general observations on water distribution could be made. Most of the water made its way on the surface of the sheathing directly down to the bottom plate. Such a pattern of water distribution results from the relatively important rate of moisture insertion. Plume patterns in the sheathing have been reported, probably resulting from much slower rates in insertion. Figure 10 shows the relative humidity in the stud cavities during the test. The figure shows that the relative humidity in the stud cavities of each wall increased at the wetting events (identified by vertical grey lines) and then decreased between them. The initial relative humidities in the cavities were 55% in OSB wall 1, 62% in plywood wall 2, and 52% in fiberboard wall 3. As the wetting phase continued, the relative humidity in the stud cavity of the plywood-sheathed wall 2 was the highest of the three walls, followed by that in the OSB wall 1 and then in the fiberboard wall 3. This occurred because the plywood sheathing panel at the top of the assembly absorbed a great deal more water than the OSB and fiberboard panels, reaching peaks of approximately 22.5% moisture content during the wetting phase, compared to about 12% for OSB and 11% moisture content for fiberboard. It should be noted that the moisture content probes in the sheathing were 7 mm (0.28 in.) long uninsulated gold pins installed from the exterior surface. The probes measure the highest moisture content from the exterior surface to a depth of approximately 6 mm (0.25 in.) from the inside surface of the panel. Water running down the sheathing is slowly absorbed by the latter, which creates a moisture gradient across the sheathing. Therefore, the innermost layers likely have a higher moisture content than what is measured by the probes. The relative humidity in the OSB-sheathed wall 1 was likely higher than that in the fiberboard-sheathed wall because its lower vapor permeability reduced the diffusive flow of moisture from week to week over the wetting phase.

The exact path of the water down the wall depended on how much was absorbed by the sheathing and held by the insulation. In general, in the fiberboard and OSB wall specimens, the surface treatment controlled water absorption by the sheathing. In effect, fiberboards are coated with asphaltic components and the manufacturing process for OSB uses industrial wax (Forintek 2001). However, in plywood, which is made of rotary-peeled veneers from logs laid in a parallel and cross layers, liquid transfer can occur more readily than in solid wood because of the possibility of liquid paths in the more open structure of the veneers (Forintek 2001), and absorption and lateral flow were observed on the face of the plywood.

Moisture Content at the Bottom of the Sheathings. Some of the sheathing gravimetric samples located in the bottom row adjacent to the bottom plate (grid "D" as shown in Figure 5) were wetted, especially for the samples in the center of the sheathing. Moisture accumulation occurred in all three sheathing materials during the wetting phase, as shown in Figure 11. The graph shows that at the end of the fourth week of wetting, the samples reached moisture contents of 21.4% to 26.9%, except for the fiberboard sample in the center of the bottom row "D" in wall 3, which was not wetted in week 4; this sample reached 50.6% at the end of week 3. Visual inspection of the wetted samples during the weighing process for gravimetry revealed that the water was first absorbed through the cut edges of the samples rather than on the surface. When inspecting the drying behavior of the different materials, it could be seen that the water absorbed by the fiberboard sample in wall 3 quickly dried out to about 15% moisture content and remained at that moisture level throughout the drying phase. The plywood sample reached 26.9% moisture content at the end of week 4 and took five days to dry to approximately 17%, at which level it remained. The OSB specimen at the center of

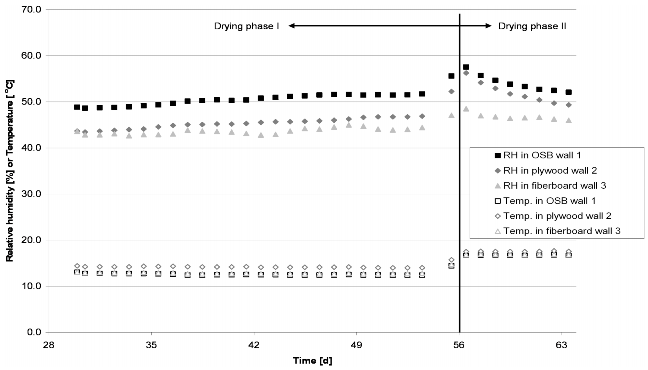

Figure 12 *Average daily relative humidity and temperature in the stud cavity at 140 mm (6 in.) from the top in walls 1, 2, and 3 in the drying phase of test 1.*

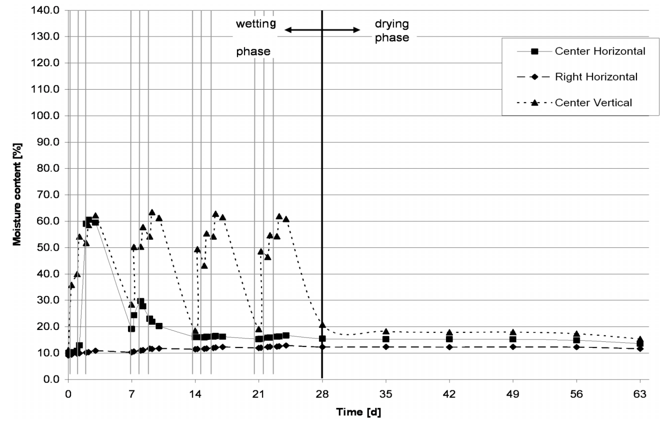

Figure 13 *Moisture content of bottom plate gravimetric samples of wall 2, which is built with plywood sheathing, in test 1.*

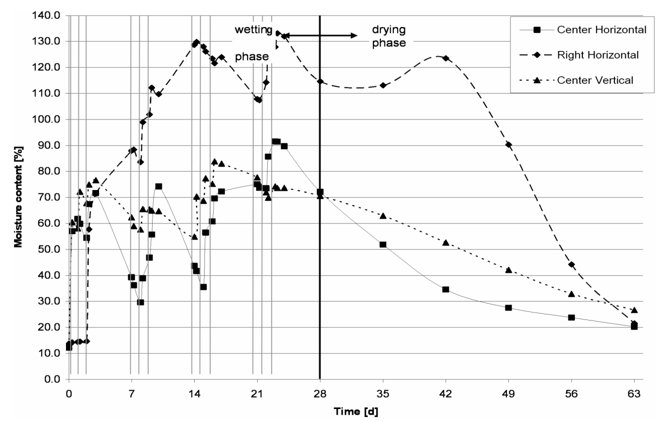

Figure 14 *Moisture content of bottom plate gravimetric samples of wall 1, which is built with OSB sheathing, in test 1.*

row "D" in wall 1 reached its highest moisture content of 26.4% toward the end of week 3 and after four days dropped to 21.5%. This sample increased in moisture content to about 23.2% in the fourth week due to the water load, and its moisture content continued to increase during the drying phase due to wetting by diffusion, reaching a maximum moisture content of about 25%. The sample dried to about 19% in the second warmer section of drying phase starting on day 56. The second OSB sample included in wall 1, located on row "D" on the right-hand side of the centerline, received less water during the wetting phase but, interestingly enough, reached moisture content values very close to the first OSB sample. A look at the relative humidity in each specimen (shown in Figure 12) explains the different equilibrium moisture content reached during the drying phase. The relative humidity in the stud cavity of all three walls increased over the duration of the first part of the wetting phase. This is likely due to the moisture within the wood components drying by diffusion and accumulating as vapor within the stud space. The relative humidities jumped in all three walls at the start of the second drying phase but then decreased because of the warmer exterior conditions.

Wetting and Drying of the Bottom Plates. Figure 13 shows the moisture content in the gravimetric samples found in the bottom plate of wall 2, which is sheathed with plywood. It can be seen that less moisture found its way to the bottom plate in this wall compared to walls 1 and 3, which have OSB (see Figure 14) and asphalt-impregnated fiberboard (see Figure 15).

The variety of the wetting pattern in the bottom plates was unexpected. In some assemblies, samples located along the centerline of the wall received water. However, in some instances, water ran down an oblique path and accumulated, not in the center of the bottom plate, but on one side. Figure 14, showing the gravimetric samples found in the bottom plate of wall 1, illustrates that the sample found on the right-hand side of the top horizontal surface reached moisture contents significantly greater than those located along the centerline of the wall. The change in the path of the water runoff may be due to the contact or lack thereof between the batt insulation and the sheathing along the path of the water. This contact can also explain why the moisture migration to a specific area may not be continuous over the four weeks of the wetting phase. For example, the gravimetric specimen in the center of the top horizontal surface of the bottom plate in wall 3 experienced moisture absorption in weeks 1 and 2 but not in weeks 3 and 4 of the wetting phase, as shown in Figure 15.

During the three days of wetting every week, the moisture content of those gravimetric samples that received water increased from day to day and subsequently tended to dry during the four "dry" days when no water was inserted. Where the samples were repeatedly wetted week after week, there is a trend of moisture accumulation in the bottom plate gravimetric samples despite the relatively small water load, as can be seen in the samples located in the center and right-hand side horizontal surface of the bottom plate for wall 1 (see Figure 14).

Table 2. Moisture Contents in Bottom Plate Inserts for Walls 1 to 3 for Test 2

Wall No.	Assembly Sheathing Material	Moisture Absorbed During Immersion [kg]	Moisture Content at End of Immersion [%]	Final Moisture Content at End of Drying [%]	Moisture Content Lost in Drying Process [%]
1	OSB	0.246	53.0	26.7	26.3
2	plywood	0.257	53.1	21.4	31.7
3	asphalt-impregnated fiberboard	0.298	56.8	20.7	36.1

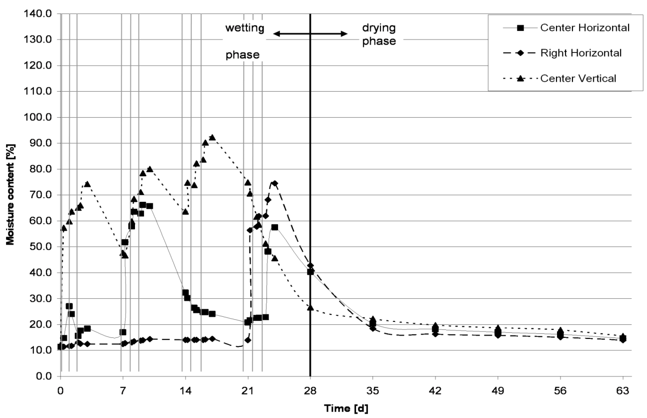

Figure 15 Apparent moisture content of bottom plate gravimetric samples of wall 3, which is built with asphalt-impregnated fiberboard sheathing, in test 1.

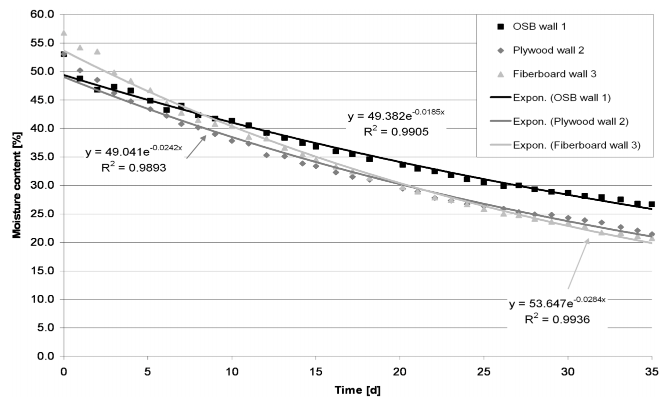

Figure 16 Moisture content in the bottom plate inserts versus time for walls 1 (OSB-sheathed), 2 (plywood-sheathed), and 3 (fiberboard-sheathed); in overlay are the fitted exponential curves.

In assembly 1, water accumulated within the fabric of the fiberglass batt insulation and then slowly made its way down to the bottom plate, which may explain the wetting of the sample found on the right-hand side of the horizontal surface (Figure 14) up to three weeks after the wetting phase had terminated.

Based on a realistic premise of rain leakage into the stud cavity from a leaky window above the assembly, the wetting method led to interesting wetting patterns and allowed some comparison between specimens. However, the moisture content values were not consistent in terms of locations and magnitude from wall to wall and a complete analysis of the role of the sheathing materials in the drying performance of the assemblies required the inclusion of drying data from a more even starting point. Hence, a different wetting method was adopted for test 2, which produced an almost uniform wetting of the bottom plate from wall to wall. The results from this test are presented next.

Test 2

Test 2 was performed on six wall assemblies. The results from three specimens are discussed here. Once again, these three walls were of identical construction with gypsum board, 140 mm (6 in.) glass fiber insulation, 6 mil polyethylene sheet, and sheathing. The sheathing panels were, respectively, for specimen 1, OSB; specimen 2, plywood; and specimen 3, fiberboard.

During the drying phase of test 2, the bottom plate inserts and the smaller four gravimetric samples were weighed once daily for 35 days using a scale with 0.01 g (2.20 × 10^{-5} lb) precision.

Moisture Content and Drying Rate of Large Inserts. Table 2 shows the total mass of moisture gained during the partial immersion of the bottom plate inserts, as well as the moisture content of each specimen after the immersion. It should be noted that since the dry mass of the inserts varies, the moisture content is a better indicator of moisture gain. Relatively uniform starting moisture contents were achieved with moisture contents within 3.8% of each other. The table also shows the moisture content at the end of the drying phases relative to the initial "dry" mass prior to immersion. It can be seen that while the insert in wall 3 absorbed the greatest amount of water compared to that in walls 1 and 2 at 56.8% moisture content, its moisture content at the end of the drying period was the lowest at 20.7%. The moisture content lost in the drying process in the fiberboard-clad wall 3 was 4.4% more than that lost by the plywood-sheathed wall 2 and 9.8% more than that for the OSB wall 1. The moisture content for the bottom plate inserts of walls 1 to 3 is shown graphically in Figure 16. The figure shows that, for all three walls, the mois-

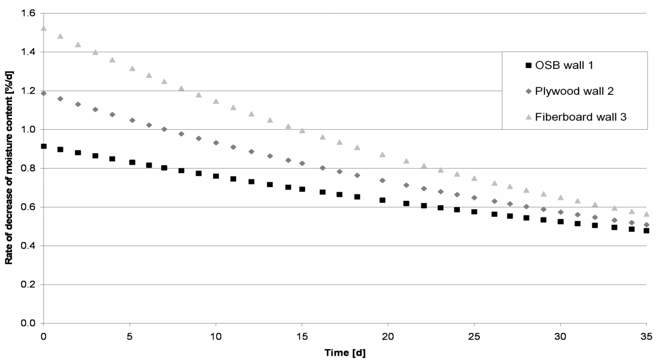

Figure 17 *Change in moisture content in the bottom plate inserts versus time for walls 1 (OSB-sheathed), 2 (plywood-sheathed), and 3 (fiberboard-sheathed), as given by the derivatives of the exponential fitted curves of Figure 16.*

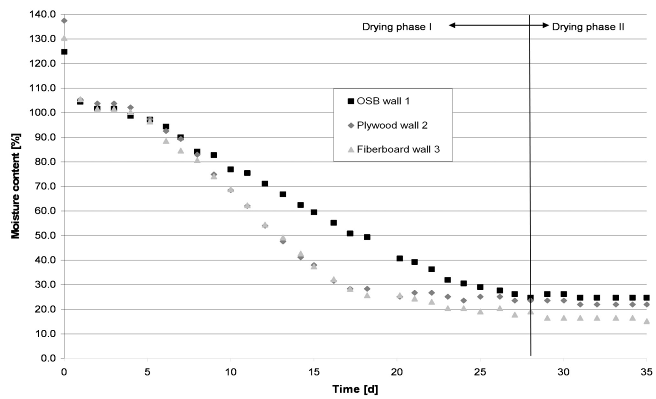

Figure 18 *Moisture content versus time of samples located at the center of the horizontal surface of the bottom plate for walls 1 (OSB-sheathed), 2 (plywood-sheathed), and 3 (fiberboard-sheathed). The samples are located 25 mm from the sheathing.*

ture content in the inserts decreased with time. The bottom plate insert with the greatest rate of drying was wall 3 with fiberboard sheathing, and although the initial moisture content of the insert in the fiberboard-sheathed wall was slightly higher, the insert dried to a final moisture content that was lower than the others. The insert with the second-fastest drying is found in the plywood-sheathed wall, followed finally by wall 1 with OSB, the order reflecting the role of the vapor permeance of the three sheathing materials. A fitted exponential curve was found for each data series, as shown in Figure 16. Correlation coefficients greater than 0.98 for each of the walls shows good correlation between the experimental data and the fitted curve. Taking the derivative of the fitted curve, the change in percentage of moisture lost with time was found and is illustrated in Figure 17. The graph shows that for all three walls, the change in the percentage of moisture lost was greater at the beginning of the drying phase and decreased with time. Initially, the change of moisture lost was highest for the fiberboard-sheathed wall at 1.5% per day, followed by the plywood-sheathed wall at about 1.2% per day, and finally the OSB-sheathed wall at 0.9% per day. At 35 days of drying, the average change in rate of drying was approximately the same for all three walls at about 0.55% per day.

Moisture Content of Small Gravimetry Samples. Graphs were also made of moisture content in time for the bottom plate gravimetric samples located at the center of the horizontal surface. This sample was on the top horizontal surface of the bottom plate along the centerline, its center lying at a distance of 25 mm (1 in.) from the sheathing. All three samples dried with time, the drying leveling off to the similar stable moisture content at the end of the test in all three walls. The curves show that these small samples, which were partially immersed for 26 days, had high initial moisture contents after immersion of about 125%, 138%, and 130% for walls 1, 2, and 3, respectively. These moisture contents quickly decreased to 105% within one day for all three samples, likely due to surface water evaporation. The drying subsequently leveled off. Contrary to the moisture content curves for the larger inserts, the drying rate of these gravimetric samples was slower over the first seven days or so, indicating that surface drying in the neighborhood of the sample was probably going on.

Comparison of the drying curves in walls 1 to 3 in Figure 18 shows that the moisture content curves of the samples in the fiberboard- and plywood-sheathed walls are virtually the same up to the 21st day of drying, denoting that both the samples exhibited the same drying rate. The lesser slope of the moisture content curve for the OSB-sheathed wall 1 illustrates that the drying rate of this sample was slower than in the other two wall assemblies. All three samples reached a similar moisture content at the end of the first drying period, which occurred during the third week for plywood and fiberboard and fourth week for the OSB samples. The last week of the test shows that equilibrium was achieved for each sample.

Two gravimetric samples were installed along the vertical centerline of the walls on the top horizontal surface of the bottom plates. The first, named Center Horizontal 1, is found at the center of the bottom plate horizontal surface with its center at 25 mm (1 in.) from the sheathing, and the second is also found along the centerline but at 25 mm (1 in.) from the gypsum, as shown in Figure 8. Given the temperature variation in the framing from the cold to the warm side of the wall, it was expected that the two samples would show the impact of temperature on the drying of the bottom plate in these locations. Analysis of the temperatures to which the samples were exposed shows that during the first drying phase, the temperature difference between the two locations ranged from approximately 3.1°C to 7.6°C (5.6°F to 13.7°F) and from 1.4°C to 5.0°C (2.5°F to 9°F) during the second drying phase

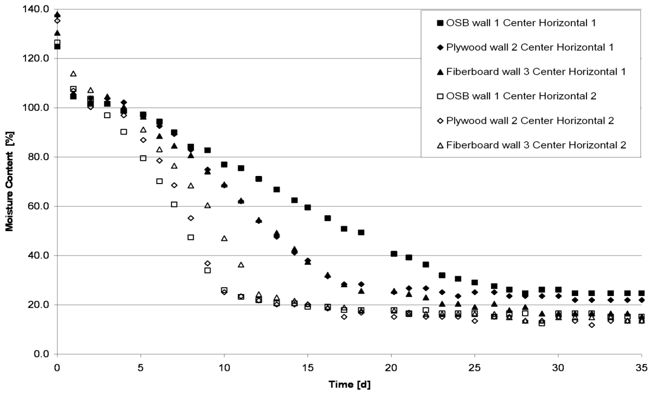

Figure 19 *Moisture content versus time in the bottom plate samples Center Horizontal 1 and 2 for wall 1 (OSB-sheathed), 2 (plywood-sheathed), and 3 (fiberboard-sheathed).*

due to the diurnally changing outdoor temperature during both phases. The moisture content of these two samples is plotted for walls 1 to 3 in Figure 19. The figure indicates that, indeed, the samples located closer to the gypsum experienced faster drying due to their warmer temperatures. In fact, these samples dried out significantly within 10 to 12 days of the start of the test, whereas the samples found near the sheathing took 16 to 23 days to reach the same moisture levels.

When comparing the drying rates of the Center Horizontal 1 and 2 samples for walls 1 to 3, the drying rate was faster closer to the gypsum board in all three walls, with the samples in the fiberboard and the plywood-sheathed walls having the highest drying rate, followed by the samples in the OSB assemblies.

DISCUSSION

Two tests were undertaken to study the wetting and drying behavior of wood-frame walls exposed to simulated rain infiltration. The wetting procedure in the first test sought to recreate as closely as possible actual wind-driven rain penetration into the stud space caused by a leak through a defect above the wall. The moisture content results show that most of the water inserted made its way to the bottom of the wall assemblies, wetting the bottom plate and the adjacent sheathing. When wetted repeatedly, there was a moisture accumulation within the gravimetric specimens after four weeks of wetting. The moisture absoption in all three sheathings depended on the sheathing type, reaching values of about 26% moisture content in the OSB samples, 50% in the plywood samples, and 51% in the fiberboard samples. Mold growth was observed on a few OSB sheathing samples 14 days into the wetting phase. Samples of all three sheathings with high moisture contents dried quickly unless exposed to a moisture load soon thereafter. During the drying phase, while plywood and fiberboard samples were quick to dry, OSB samples did not dry initially and even slightly increased in moisture content after the wetting phase, to dry out in the second warmer portion of the drying period. These findings generally reflect those of Ojanen (1998), Zarr (1995), and Hazleden and Morris (2001), although results are difficult to compare because of the different wall setups and configurations, moisture sources, environmental conditions, and monitoring methods.

Results from the first test show that the moisture distribution from wall to wall was variable, accumulating within the insulation and running down the sheathing down the centerline and along an oblique path. In addition, results show that some samples were not wetted at each wetting event. More analysis is required to investigate the variety of patterns obtained and their relevance. In any case, the method succeeded in producing a distributed realistic water load of small to medium magnitude. However, this method created conditions within the assembly that did not produce uniform moisture loading from wall to wall.

A different wetting procedure was undertaken in test 2 in order to generate uniform wetting in all the wall assemblies where bottom plate inserts and smaller gravimetric samples were partially immersed. Moisture content results for the bottom plate inserts showed that inserts installed within the fiberboard-sheathed wall dried faster, followed by the plywood-sheathed wall and then the OSB insert, as demonstrated by the moisture content and the change in moisture content over time. Analysis of the change in moisture content in time shows that the rate of drying for the fiberboard sample was the fastest, followed by the rate in the plywood specimen, while that for the OSB assembly had the slowest rate. However, at the end of the five-week drying period, all inserts reached very similar moisture content levels. Results have also shown that the temperature gradient has a significance on drying, as shown by the drying moisture content curves of two samples located on the top horizontal surface of the bottom plates. More analysis of the impact of different parameters is required to evaluate whether the different wall assemblies behave satisfactorily in light of the moisture loads to which they were subjected.

Air leakage of warm, moist indoor air through cracks and other defects in the building envelope can be an important contributor to wetting of assemblies, especially when it comes in contact with cold surfaces such as a wall sheathing and condenses. In this case, the air pressure difference between the two sides of the wall is the driving force for such air movement. In the experiment, the access doors in the gypsum interior finish, as shown in Figure 2, as well as the gap between the wall sheathing gravimetric samples and the sheathing boards themselves, provided openings through which air could have entered the envelope assemblies. While air leakage tests were not attempted, the air pressure difference between the indoor and outdoor of the test hut ranged between −1 Pa to +3 Pa, suggesting that the effect of air leakage on the hygrothermal performance of the assemblies was insignificant compared to the liquid moisture source.

CONCLUSION

An experimental investigation was performed to study the hygrothermal response of North American residential wood-frame walls with different wood-based sheathings subjected to water penetration. This paper presents the results of three tests. Specifically, the role of the sheathing was examined in walls that were subjected to two different wetting methods simulating wind-driven rain infiltration. In the first wetting method, water was inserted into the top of the stud space in a drip fashion, where it ran down the inside surface of the sheathing and accumulated on the bottom plate and adjacent sheathing. In the second wetting method, bottom plate inserts and gravimetric specimens were initially partially immersed in a shallow pool of water and then installed within the wall assemblies. While the second method is easier to apply and produces more repeatable results that are easier to analyze, the first method is more realistic in that it simulates the occurrence of some types of leaks into the back wall at a point source.

Moisture content measurements by gravimetry were taken to evaluate the wetting performance of the assemblies and evaluate the role of the sheathing material in drying. The results have repeatedly shown that wetted samples in the walls sheathed with fiberboard had the highest drying rates, likely due to the higher vapor permeability of fiberboard. The moisture content of the gravimetric samples within the OSB-sheathed assemblies repeatedly showed the slowest drying rates. However, at the end of the five-week drying period, all samples dried to a similar moisture content level. The data also showed that a temperature gradient had a significant impact on the drying rate. The findings will lead to providing the construction industry with guidelines to the optimized use of different sheathings.

ACKNOWLEDGMENTS

The authors are grateful for the financial support provided by the EJLB Foundation, Forintek, Société d'Habitation du Québec, and the Natural Science and Engineering Research Council of Canada (NSERC), and to Dr. Jiwu Rao for his assistance in the deployment of the test facility and instrumentation.

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