Reprinted from JTE, Vol. 39, No. 3
doi:10.1520/JTE102973
Available online at www.astm.org/JTE

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Moisture Response of Sheathing Board in Conventional and Rain-Screen Wall Systems with Shiplap Cladding

ABSTRACT: Building enclosures are subjected to a random climatic loading on the exterior surface and a relatively stable indoor condition on the interior. These loadings result in a transport of heat, air, and moisture across the building enclosure. In this paper, the drying and wetting of sheathing board in two exterior walls, more specifically 2×6 in.^{2} wood-frame conventional (no strapping between sheathing membrane and cladding) and a rain-screen wall system (with vertical strapping), are investigated through an experimental field study. The experiment is carried out at British Columbia Institute of Technology field exposure test facility, where the test walls are exposed to the coastal climate (Vancouver weather) on the exterior and controlled indoor temperature and relative humidity conditions in the interior. The field experimental results indicate significant moisture accumulation on the exterior sheathing boards (plywood) during the Winter period. During the 9-month monitoring period from March 13 to Dec. 6, 2009, the plywood underwent a process of drying and wetting. In both the conventional and rain-screen wall systems, the plywood dried to a comparable moisture level during the Summer before the wetting process started. For the wall systems considered in this study, the plywood in the rain-screen wall has a tendency of faster drying and wetting in the Spring and Fall seasons, respectively, in comparison to the plywood in the conventional wall, which is attributed to the presence of an air gap in the rain-screen wall between the sheathing membrane and the cladding. A similar trend is observed during the monitoring period from December 7 to June 15, 2010.

Manuscript received January 14, 2010; accepted for publication August 14, 2010; published online October 2010.

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Cite as: Tariku, F. and Ge, H., “Moisture Response of Sheathing Board in Conventional and Rain-Screen Wall Systems with Shiplap Cladding,” *J. Test. Eval.*, Vol. 39, No. 3. doi:10.1520/JTE102973.

KEYWORDS: rain-screen wall, cavity ventilation, field-experiment, hygrothermal performance, wetting and drying potentials

Introduction

Excessive moisture in the building envelope reduces a building's durability and compromises the quality of the indoor environment. Rain load is one of the most important outdoor climatic parameters and rain penetration is the major source of moisture in building envelopes, which has led to extensive building failures in the region of Lower Mainland British Columbia and other countries with similar rain conditions [1]. The massive building envelope damage in British Columbia in the 1990s, which is well known as Vancouver's leaky-condo crisis, was estimated to be $1 billion [2]. In response to this massive building failure crisis, the National Building Code [3] and the Provincial Building Code [4] enforce "rain-screen wall" design, which creates a capillary break and drainage plane between the first line of defense (cladding material) and second line of defense (sheathing membrane), in the wet climate regions. The airflow through the capillary break gap might facilitate wetting or drying of the cladding and the sheathing membrane depending on the climatic conditions and the orientation of the wall system.

Extensive research has been done on evaluating the moisture removal by cavity ventilation through laboratory testing, field measurements, and simulations [5–12]. The general conclusions are that ventilation drying is beneficial for wet panel cladding and for solar-driven inward vapor diffusion in Summer. The drying provided for Winter is minimal. The climate in southern British Columbia is characterized by a long rainy Winter. Whether the provision of a ventilation cavity in the rain-screen wall can assist the drying for this particular climate is the focus of this study. This study assesses the drying and wetting potentials of sheathing boards in two wall systems: One with no strapping, referred in this paper as "conventional wall system," and a rain-screen wall with 19 mm strapping that provided air gap between the shiplap cladding and the sheathing membrane. The study is carried out at British Columbia Institute of Technology's (BCIT) field exposure test facility (Building Envelope Test Facility (BETF)), where the test wall panels are installed and their hygrothermal responses to Vancouver weather conditions and controlled indoor climatic conditions are collected along with the respective hygrothermal loadings

When the wall systems were installed on the field exposure test facility in July 2008, the electrical resistance measurement method, with a 100 MΩ resistor in parallel with moisture pins, was adapted for moisture content (MC) measurement of the plywood. Inspection of the measured data suggested that the MC reading with the adapted method was high and unreliable. On March 13, 2009, the MC measurement wiring was switched to a series circuit with a 5 MΩ resistor, a method that is commonly used by other researchers [13–15]. In this paper, the measurements obtained after March 13, 2009, are used for discussion.

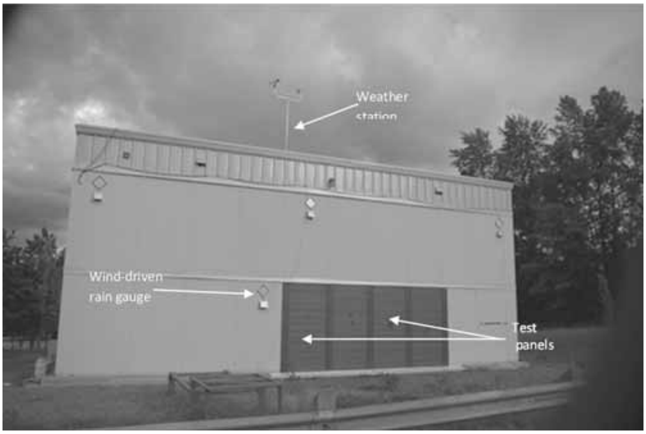

FIG. 1—*BCIT's BETF* (*northwest view*).

Field Experiment

Test Facility

The experimental study is being carried out at BCIT BETF (photo shown in Fig. 1). The research facility is designed to evaluate the hygrothermal performance of full-scale building envelope assemblies under simulated indoor and real climatic outdoor conditions. The $44 \times 28\ \text{ft}^2$ two-story structure can accommodate in total 62 $4 \times 8\ \text{ft}^2$ ($1.2 \times 2.4\ \text{m}^2$) panels. The panels are removable, allowing for ease of implementation of any type or location of testing required. Two mechanical systems are fitted within the facility allowing the separation of interior spaces into two conditioned horizontal zones, thus allowing control of the indoor boundary conditions, namely, temperature and relative humidity, at the desired values. Each system can maintain indoor temperature within the range of $18-26\,^\circ\text{C}$, with a precision of $\pm 2\,^\circ\text{C}$, and relative humidity within the range of 40–80 %, with a precision of ± 5 %. The facility is equipped with a data acquisition system with over 600 channels, allowing for the monitoring of hygrothermal conditions within wall assemblies including temperature, relative humidity, MC, heat flux, air velocity, wind-induced pressure, and incidence of condensation and rain penetration. The facility is also equipped with a weather station mounted on the rooftop of the facility to measure the outdoor boundary conditions including wind speed, wind direction, solar radiation on both horizontal and vertical surfaces, and horizontal rainfall. Driving rain on wall surfaces is also collected. More information about this facility can be found in Ref 16.

Test Panels and Instrumentation

Two $4 \times 8\ \text{ft}^2$ test panels were fabricated as conventional and rain-screen wall systems and installed in the northwest section of the BETF. The configuration

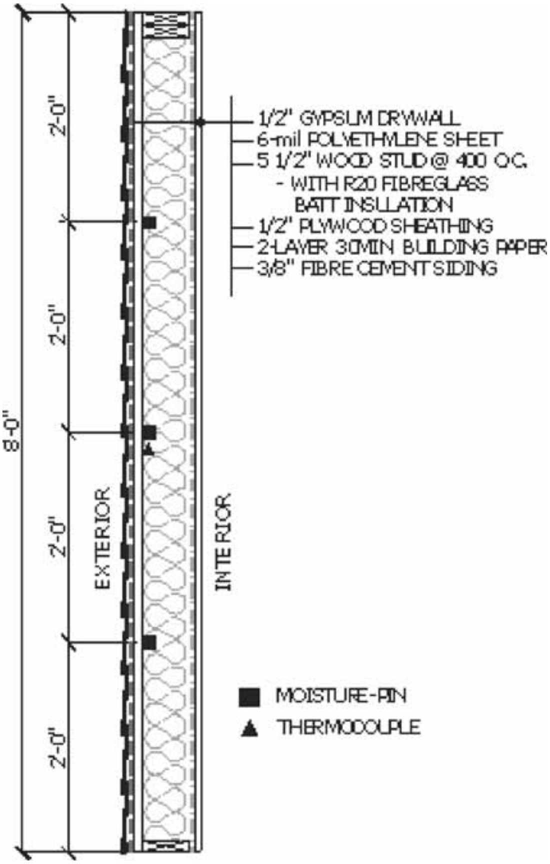

FIG. 2—*Vertical cross-section of the instrumented conventional wall system.*

of the $2 \times 6\ \text{in.}^2$ ($38 \times 140\ \text{mm}^2$) wood-frame test panels from exterior to interior, in sequence, is as follows: Horizontal shiplap fiber cement siding, two layers of 30 min rated asphalt-impregnated building papers as a weather barrier, 12.5 mm plywood as a sheathing board, 138 mm glass fiber insulation, 6-mil polyethylene sheet as a vapor and air barrier, and interior finish (gypsum board, 12.5 mm). The rain-screen wall has a 19 mm air gap between the sheathing membrane and cladding. The schematic diagrams of the vertical cross-sections of the conventional and rain-screen walls, along with the corresponding sensors that are installed to measure the MC and temperature of the plywood, are shown in Figs. 2 and 3, respectively.

The cores of the test walls including framing, insulation, polyethylene sheet, and plywood sheathing were fabricated and instrumented in a controlled environment in mid-June 2008, and therefore, a good workmanship has been achieved. The test panels were stored inside the shop for about 1 month before being installed on the test facility, therefore, the initial MC of plywood sheathing boards and wood-frame members can be deemed uniform. The building

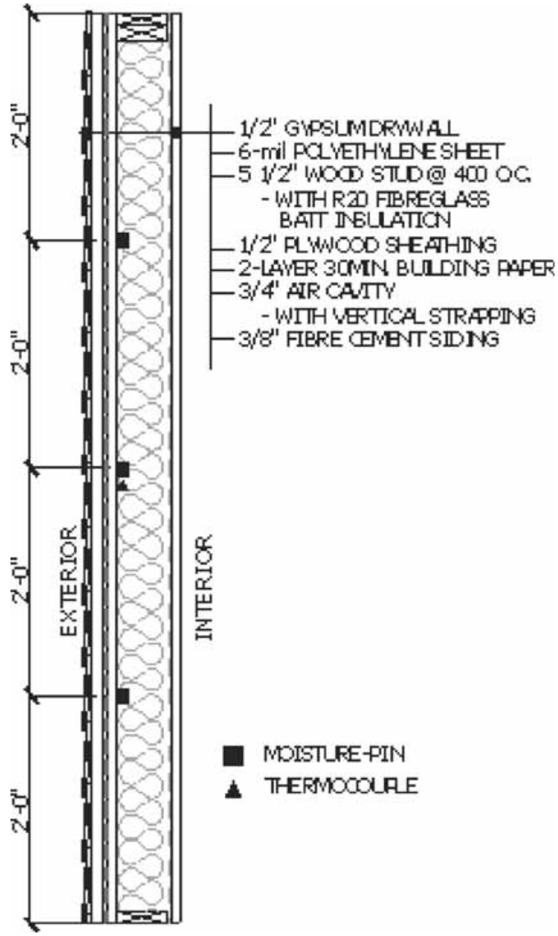

FIG. 3—*Vertical cross-section of the instrumented rain-screen wall system.*

papers, the cladding (fiber cement siding), and the interior layer (gypsum board) were installed after the walls were in place on the test facility. To provide the thermal and moisture separation from the surrounding existing walls, the polyethylene sheet was wrapped around the edge of the stud to overlap with the building papers. The 2 in. gap between each test wall was fitted with rigid insulation and sealed to the side with sealant and backing rod.

To measure the MCs of the plywood during the monitoring periods at different heights, three pairs of moisture pins were installed on each test panel from the inside along its center line. The three moisture measurement points were at the lower, middle, and upper position, more specifically, at the one-quarter, half, and three-quarter wall height. Figures 2 and 3 show the locations of the moisture pins along with the thermocouple, which were installed at the middle height of the wall. In addition to providing information about the thermal responses of the two wall systems, the thermocouple readings are used for conversion of the three electrical resistance measurements of the corresponding wall systems. The MC measurement system was developed and calibrated in the building science laboratory of BCIT with an accuracy of 2 % in the range of 6–25 % MC. This system was used in a previous study [14], in which both gravimetric and moisture pin measurements were taken and the discrepancy is within 2 % [12].

30-gauge premier grade type T (copper and constantan) thermocouple wires were used to measure temperature. They were calibrated by using an isothermal bath (accuracy of ±0.1 °C) with Agilent Switch Unit (model 34970A) at three different temperatures: 10, 20, and 30 °C. The system measurement accuracy is ±0.5 °C. The MCs of plywood and stud were measured by using electric moisture pins. The moisture pins are stainless steel screws and, using gravimetric samples, the measuring system was calibrated to a range of 6–25 % for plywood and 7–30 % for wood stud with an accuracy of ±2 %. The MC and temperature measurements are scanned every 5 min and recorded by the data acquisition system.

Climatic Conditions

The test panels are exposed to Vancouver weather conditions on the exterior and controlled indoor temperature and relative humidity conditions on their interior surfaces. The local outdoor climatic conditions including temperature, relative humidity, wind speed and direction, global solar radiation, and horizontal rainfall are measured with a weather station that is mounted on the rooftop of the BETF. The wind-driven rain that impinges the test panels is also measured with a rain gauge that is vertically mounted adjacent to the test panels. The measured climatic conditions are presented and discussed in the Results and Discussion section.

The indoor temperature and relative humidity conditions are controlled by thermostat and humidistat, respectively. The temperature set point is 21 °C and has been kept constant throughout the monitoring period. The test facility is equipped with humidification systems and it is possible to control the indoor relative humidity during the Winter period. But, as can be seen in Fig. 4, the indoor relative humidity during the Summer period is considerably higher than the set point of 40 %. This is due to the fact that the ventilation fan was continuously running and there is no dehumidification unit to remove the excess moisture. Moreover, the moisture removal by the air conditioning unit might have been limited due to the mild outdoor temperature and part-load operation of the equipment, which generally happens in mild, wet climates like Vancouver. The maximum relative humidity inside the BETF during the Summer period was 71 %, which was recorded on July 28, 2009.

Results and Discussion

In the wall systems considered in this study, the sheathing board is the critical layer that is susceptible to moisture damage due to high moisture accumula-

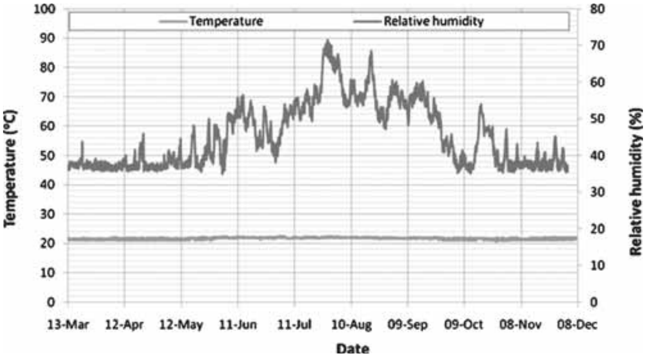

FIG. 4—*Indoor temperature and relative humidity of the BETF.*

tion. Thus, the MC and temperature of the plywood in the two different wall systems are discussed.

Figure 5 shows the MC of the sheathing board in the conventional wall system. The MC of the plywood at the upper position is consistently higher than at the middle and lower positions. In fact, until the end of April, the MC at the upper position is higher than the 19 % MC level that is recommended to avoid moisture related durability problems. In the first two months, the plywood was in a slow drying process. During this period, the indoor temperature and relative humidity were relatively stable at 21 °C and 36 %, respectively (Fig. 4), and the exterior surfaces of the walls were exposed to ten wind-driven rain events (all under 0.1 mm/h, Fig. 6), higher outdoor relative humidity (Fig. 7) and low solar radiation (Fig. 8), which might have contributed to slow drying of the sheathing board. The drying process accelerated in the month of May as the ambient temperature (Fig. 7) and solar radiation increased. The MC changes in the plywood during the Summer months of June and July were minimal. This is expected since the material was relatively dry and further drying was a very slow process. During this period, the ambient temperature and solar radiation

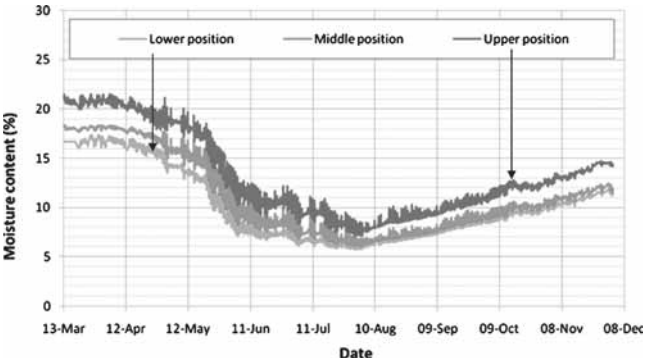

FIG. 5—*MC of the sheathing board (plywood) in the conventional wall system at the lower, middle, and upper positions.*

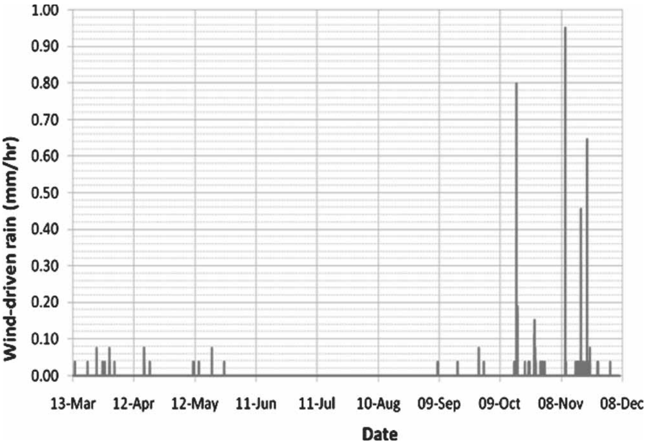

FIG. 6—*The hourly wind-drive rain load on the test walls collected by a wind-driven rain gauge next to the test panels.*

as well as the indoor relative humidity were rather high, and there were no wind-driven rain events (see Fig. 4 and Figs. 6–8). The effect of indoor vapor pressure on the drying process is expected to be low since there is a 6-mil polyethylene sheet behind the interior layer (gypsum board) and good workmanship was achieved in constructing the test wall. The MC of the plywood starts to increase at the beginning of August and continues through the Winter period. The plywood's MC increase during the late Summer and Fall seasons is due to the reduction in the ambient temperature and solar radiation, which reduce the plywood temperature, coupled with the presence of relatively humid air.

As can been seen in Fig. 5, the MC difference between the upper and lower positions on March 13 is about 4 %. The difference slowly decreases, reaching the lowest value of 2 % at the end of July, and then increases during the Fall season to 3 %. The MC of the plywood at the middle section is slightly higher

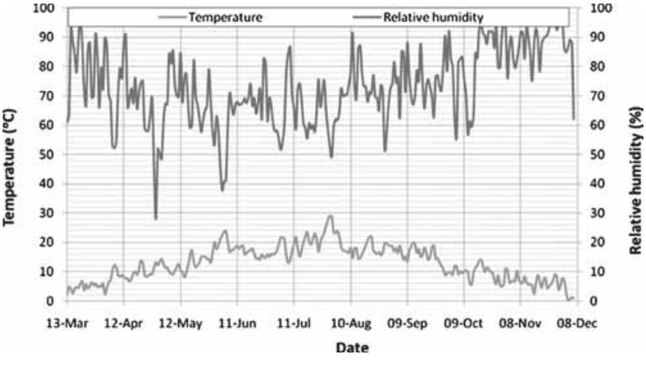

FIG. 7—*The daily average outdoor air temperature and relative humidity.*

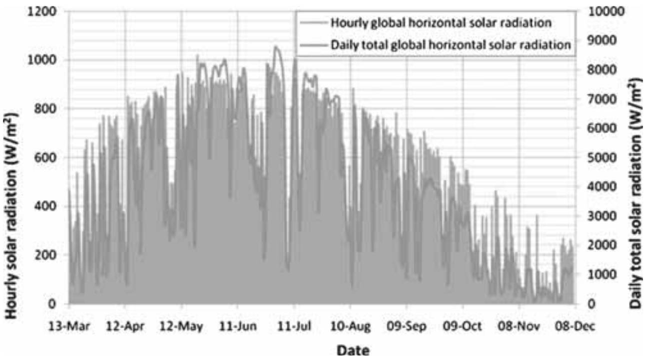

FIG. 8—*The hourly average and daily total horizontal global solar radiation.*

than at the lower section. The difference in MC between upper and middle positions is slightly higher than that between middle and lower positions. A number of factors may have contributed to the vertical profile of MC in plywood such as convection loop within insulation cavity, higher moisture exposure on cladding at the upper level due to wind-driven rain, and under-cooling induced surface condensation; however, further investigation is required before the actual cause can be identified. Tables 1 and 2 show the maximum and minimum MC readings, as well as the maximum MC changes, observed during the drying (March 13 to Aug. 1, 2009) and wetting (August 1 to Dec. 6, 2009) periods, respectively. Although the lowest MC reading during the drying period (Table 1) is at the lower position (5.8 %), the drying rate is higher at the upper section of the plywood (14.4 %). During the wetting period, the upper position also has a higher wetting rate (8.1 %) compared to the lower and middle positions (6.1 % and 6.6 %, respectively).

Figure 9 shows the drying rates of the upper and middle positions of the plywood. The drying rates are relatively high during the month of May and June. The maximum drying rate is 0.19 % per day corresponding to May 26, 2009, and decreases as the plywood gets drier (below 70 % relative humidity). In general, the upper section of the plywood shows a relatively higher drying rate in July and a higher wetting rate in October as compared to the middle section.

Figure 10 shows the hourly and daily average temperature measurements of the plywood's interior surface at the middle section. The daily average ambient air temperature is also superimposed on the figure. During the March 13

TABLE 1—*Extreme MCs of plywood sheathing in conventional test wall during the drying period (March 13 to August 1).*

Moisture Content	Lower Position	Middle Position	Upper Position
Maximum (%)	16.8	18.4	21.5
Minimum (%)	5.8	6.0	7.1
Difference (%)	**11.0**	**12.4**	**14.4**

TABLE 2—*Extreme MCs of plywood sheathing in conventional test wall during the wetting period (August 1 to December 6).*

Moisture Content	Lower Position		Middle Position	Upper Position
Maximum (%)	11.9		12.6	15.2
Minimum (%)	5.8	29	6.0	7.1
Difference (%)	**6.1**		**6.6**	**8.1**

to Dec. 6, 2009, monitoring period, the surface temperature of the plywood varies from the lowest value of −5.8°C on December 2 to 62.8°C on July 21. The daily average temperature difference between the ambient air and the plywood is higher during the Summer months when the solar radiation is high.

Figure 11 shows the MC of plywood in the rain-screen wall system at the lower, middle, and upper positions. Prior to April 8, the MC measurements of the plywood at the upper location were over 25 %. Since the measurement method adopted in the study does not yield reliable readings for MC over 25 %, the respective data is excluded from the analysis. In general, the plywood's MC in Fig. 11 can be categorized into three sections: Drying period (March 13 to June 4), stable period (June 4 to August 4), and wetting period (August 4 to December 6). Faster drying is observed at the upper section of the plywood followed by the middle and lower sections, respectively. During the stable period of two Summer months, the MC of the plywood decreases by only 2 %. During the wetting period, the MC of the plywood at the upper section increases significantly more than the middle or lower sections. This might be attributed to an air leakage at the upper section of the test panel where the measurement wires are routed out of the test panel to be connected to the data acquisition system.

Relative Comparison of the Drying and Wetting Potentials of Plywood in the Conventional and Rain-Screen Wall Systems

The MC and temperature readings at the middle positions of the conventional and rain-screen walls are used to assess the relative drying and wetting poten-

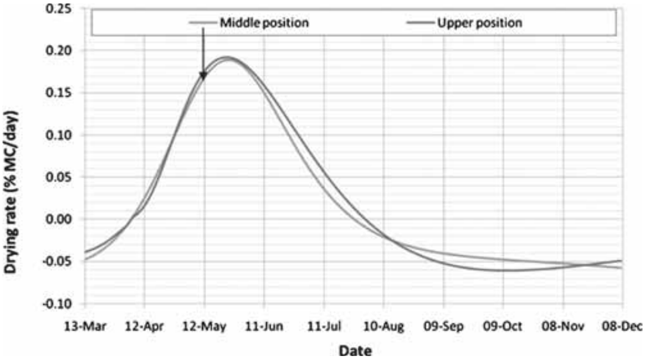

FIG. 9—*Drying rate curves of the upper and middle positions.*

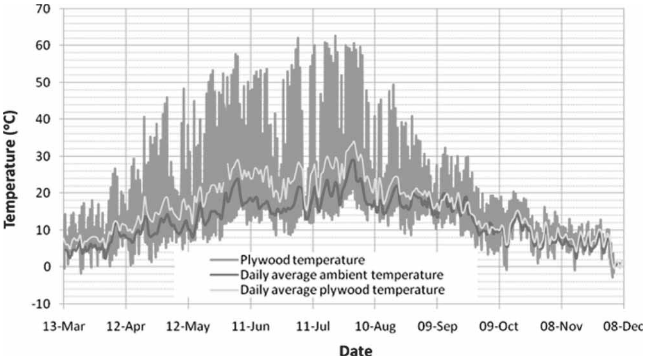

FIG. 10—*Plywood's interior surface and outdoor air temperatures in the conventional wall system.*

tials of the plywood in the two wall systems. Figures 12 and 13 show the daily average MC and the drying rate curves of the plywood in the conventional and rain-screen wall systems, respectively. Although the plywood in the rain-screen wall starts with slightly higher MC, by June 4 it reaches lower MC compared to the conventional wall due to its higher drying rate as shown in Fig. 13. The higher drying rate might be the result of extra moisture removal from the wall by the airflow through the gap between the sheathing membrane and the cladding. During this period (March 13 to June 4), the daily average MC of the ambient air, shown in Fig. 14, is below 8.0 g/kg, and can potentially remove moisture from the moist sheathing membrane and thereby result in lower MC in the plywood.

Figure 15 shows the monthly total wind-driven rain on the prevailing wind-driven rain direction (southeast) and test wall direction (northwest) for March to November 2009. Since the test walls discussed in this paper were installed in the northwest orientation, which is opposite to the prevailing wind-driven direction, the amount of the wind-driven rain that impinges the exterior surfaces

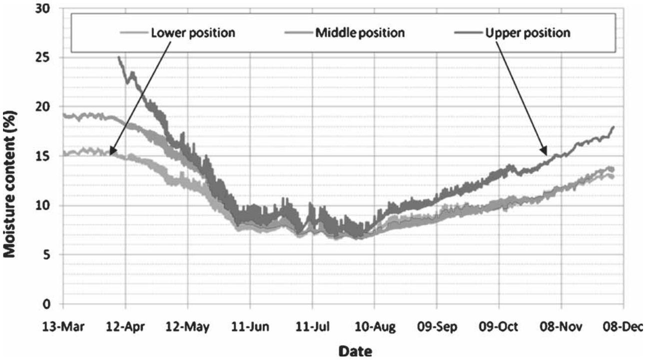

FIG. 11—*Transient MC of the sheathing board (plywood) in the rain-screen wall system at the lower, middle, and upper positions.*

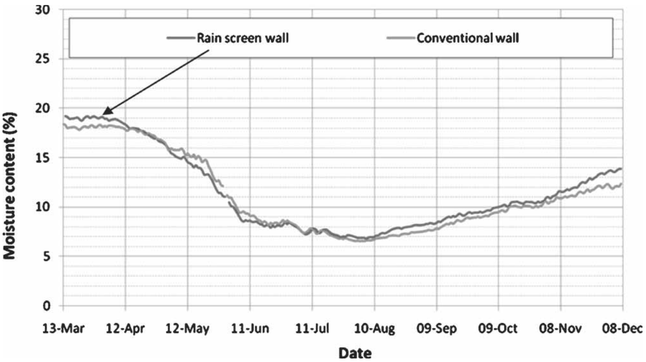

FIG. 12—*MC of the plywood in the conventional and rain-screen wall systems* (*data presented is the daily average of the middle location*).

of the test walls is significantly lower (in most cases under 0.1 mm/h) and, in some months, none at all. For example, between April 26 and September 8 (see Fig. 6), the test walls were not exposed to wind-driven rain load, although there were rain events during the same period of time as shown in Fig. 16. Between March 13 and December 6, 2009, the maximum wind-driven rain load is 0.95 mm/h, which is about one-seventh of the horizontal rain that is recorded in the same rain event. The insignificant wind-driven rain exposure of the test walls suggests that the prominent effect of the air gap in the experimental study reported here might be more on providing cavity ventilation than providing capillary break or drainage. The effect of the air gap in walls in other orientations or climatic conditions can be different, and possibly result in higher variations of moisture accumulation between the conventional and rain-screen wall systems than observed in this study.

During the following two months (June 4 to August 4), the drying rate of the plywood in the rain-screen wall is lower than in the conventional wall (see Fig. 13). This effect is also probably related to the airflow through the cavity in

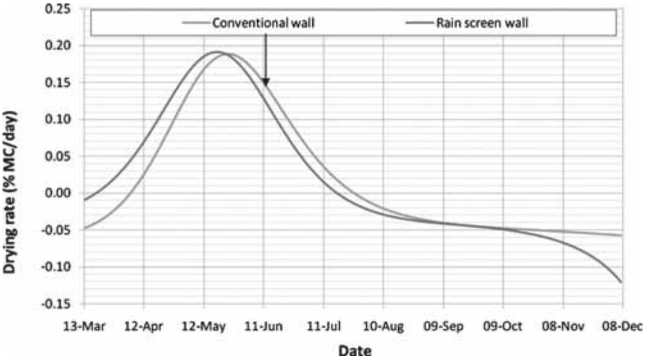

FIG. 13—*Drying rate curves of the plywood in the conventional and rain-screen wall systems* (*middle location*).

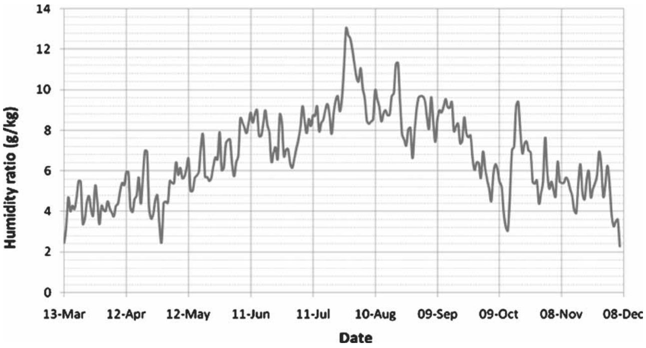

FIG. 14—*The daily averaged absolute humidity ratio of the outdoor air.*

such a way that the air that flow through the cavity during the Summer period has high vapor pressure (as reflected in Fig. 14 as high humidity ratio with a maximum value of 13 g/kg on July 26) and can also have had the effect of cooling the plywood (Fig. 18) and thereby reducing the drying capacity of the plywood by vapor diffusion. During the wetting period (after August 4), the MC of the plywood in the rain-screen wall increases more than the conventional wall. Also, the heat gain due to solar radiation and ambient temperature, as well as the plywood temperature, are continuously decreasing, which may facilitate moisture accumulation as the moist air flows through the cavity. The drying rate curve (see Fig. 13) shows further increase in the wetting rate of the plywood in the rain-screen wall in the month of November

To assess the long-term moisture responses of the sheathing boards in the two wall systems, the experimental study was extended for another 6 months (December 2009 to June 2010). The MC of the middle section of the sheathing boards in the conventional and rain-screen wall systems during the 15 months monitoring period are presented in Fig. 17. Similar to the discussion already

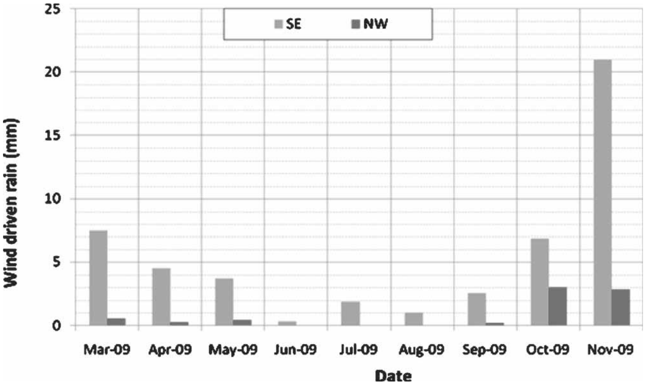

FIG. 15—*Wind-driven rain on the prevailing wind-driven rain direction (southeast) and test wall direction (northwest).*

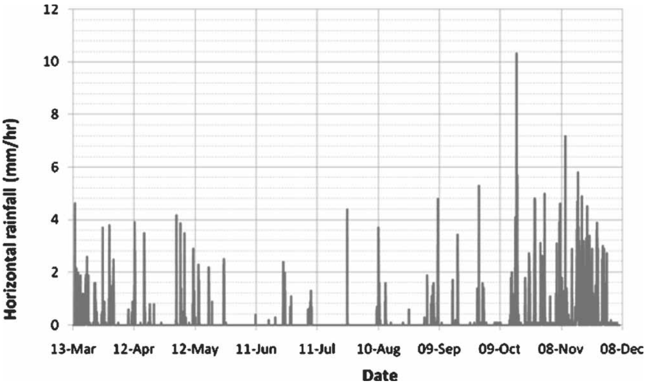

FIG. 16—*The hourly rainfall (horizontal rain) measured at the roof top of the BETF.*

presented in the Relative Comparison of the Drying and Wetting Potentials of Plywood in the Conventional and Rain-Screen Wall Systems section, the plywood in the rain-screen wall system reaches to its peak MC sooner than the plywood in the conventional wall, and started drying two weeks in advance. The two sheathing boards' peak MCs differ by only about 1 %, and in general, the MC differences in the two sheathing boards during the 15 months monitoring period are insignificant. This can be attributed to the test panels' orientation that lead to minimal wind-driven rain load exposure and the type of cladding used in the study. In the conventional wall system, the shiplap cladding provides compartmentalized airspace (which would not exist in other type of cladding such as stucco cladding) that can have an effect in the drying and wetting processes of the sheathing board.

The temperature of the plywood in the rain-screen wall is similar to that of the plywood in the conventional wall (see Fig. 10). To investigate further, the temperature difference between the interior surfaces of the plywood in the two wall systems is plotted in Fig. 18. In the same figure, the daily total solar radia-

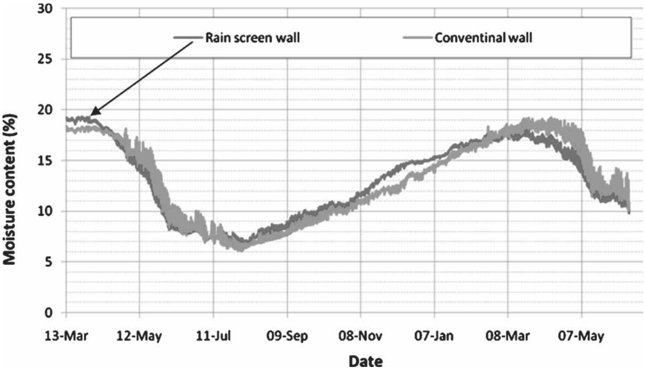

FIG. 17—*MC of plywood sheathing boards in the conventional and rain-screen wall systems from March 13, 2009, to June 15, 2010.*

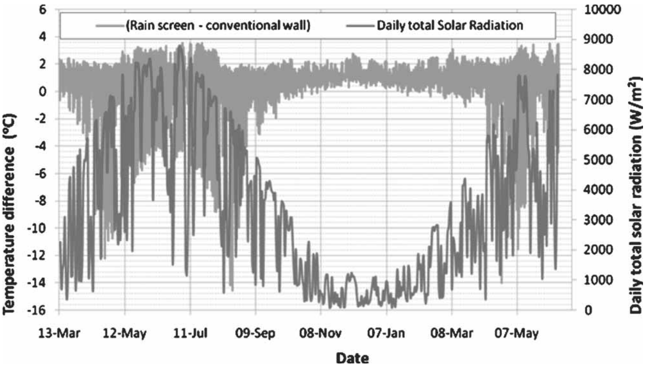

FIG. 18—*Temperature difference between the plywood in the rain-screen and conventional wall systems and the daily total solar radiation.*

tion is also plotted. As can be observed from the figure, the temperature difference in the two walls seems to depend on the magnitude of solar radiation. When the solar radiation is low, so is the temperature difference. Moreover, at high solar radiation the plywood in the rain-screen wall has a relatively lower temperature than the plywood in the conventional wall system. Since there was no airflow measuring probe installed in the current experiment, it was not possible to verify whether higher solar radiation increases cavity ventilation and, consequently, results in cooling of the plywood. In theory, cavity ventilation may result in cooling or heating of the sheathing layer when the exterior surface of the cladding receives high solar radiation or loses significant heat by long-wave radiation heat exchange with the sky and surroundings, respectively. This is because the ambient temperature will be lower compared to the sheathing layers during high solar gain, and the converse is true for the case of significant heat loss by long-wave radiation. At low or an absence of solar radiation, the latter may dominate and may result in a relatively higher temperature reading in the rain-screen wall sheathing layer compared to the conventional wall. In the result presented in Fig. 18, the hourly average temperature of the plywood in the rain-screen wall is higher than in the conventional wall for 75 % of the monitoring period. The temperature deviations of the two wall systems during this part of the monitoring period are relatively small (less than 3.5 °C). During the rest of the monitoring period, the temperature differences are relatively high and occur between 4 p.m. and 7 p.m. in the afternoon, which may be associated to the high solar radiation that reaches the test walls as they are oriented in the northwest direction. At this time, the ambient air will be at a lower temperature compared to the sheathing layer temperature and may provide cooling to the sheathing layer as it passes through the rain-screen wall air gap.

Conclusion

An experimental study of the drying and wetting processes of the sheathing boards in the conventional and rain-screen wall systems was carried out at

BCIT's field exposure test facility. Similar drying and wetting processes are observed in both wall systems. For the wall types, orientations, climatic conditions, and monitoring period considered in the study, the MCs of plywood at the middle and lower positions have relatively low MC readings compared to the upper position, but the upper position has the highest drying rates and reaches the same MC level as the other two positions at the beginning of the Summer season. An analysis of the drying and wetting of the sheathing boards suggests that the plywood in the rain-screen wall has a tendency of faster drying and wetting in the Spring and Fall seasons, respectively, in comparison to the plywood in the conventional wall. The airflow through the air gap in the rain-screen wall system might have facilitated the drying and wetting processes. But, in the Summer, the plywood in both wall systems dried to about the same level of MC.

In the experimental study reported here, the prominent effect of the air gap in the rain-screen wall system might be more on providing cavity ventilation than providing capillary break or drainage since the wall systems were exposed to wind-driven rain loads of low magnitude. The effect of the air gap in walls in other orientations, cladding type or climatic conditions can be different, and possibly result in higher variations of moisture accumulation between the conventional and rain-screen wall systems than observed in this study.

Acknowledgments

The writers would like to acknowledge the financial support received from the School of Construction and the Environment, BCIT, and Pacific Building Systems and the assistance of Stephen Roy and Wendy Ye.

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