Large-Scale Experimental Investigation of Wood-Frame Walls Exposed to Simulated Rain Penetration in a Cold Climate

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ABSTRACT

As rain can be the most important potential source of moisture in wall assemblies, an experimental investigation compares the wetting and drying patterns of 15 walls subjected to simulated rain penetration in the stud cavity.

A 2-story test hut was built within a large Environmental Chamber to receive 31 wall specimens of 2'-4" x 8' (0.9 m x 2.4 m). The 15 specimens discussed in this paper consider three different types of sheathing – oriented strand board (OSB), plywood and fiberboard, two exterior claddings – wood cladding on furring and cement stucco on metallic lath (no air space), and two different interior finish permeances – paint with/without polyethylene sheet. The walls were built with 2" x 6" (38 mm x 140 mm) studs and insulated with glass fiber insulation. The moisture content of the bottom plate and sheathing in each wall was monitored using moisture content probes and gravimetric measurements. The exterior conditions were controlled to reproduce August through November weather conditions for Montreal. The interior conditions were maintained at 21ºC and 40% RH. To simulate rain penetration conditions, the wall specimens received a wetted insert, i.e. a wetted bottom plate, at the beginning of each climatic period.

Gravimetry results obtained for the different wall specimens are presented and discussed. The moisture content distribution and levels in the bottom plates and sheathing through the four climatic sets of conditions show an increase in spread as conditions are cooler. The potential influence of the sheathing material, of the cladding with and without air space, and of the level of permeance of the interior finish is discussed. Overall, the walls with stucco cladding retained greater moisture content than those with a furred wood cladding.

INTRODUCTION

Characterization of the wetting/drying process in wood-framed building envelopes submitted to water penetration is especially relevant where environmental conditions are less forgiving. Examples of major building failures in such types of climate have occurred over the last years in Vancouver, Seattle, and North Carolina, for example (Barrett 1998, Karagiozis and Desjarlais 2003). Combined with environmental conditions, factors like faulty or inappropriate wall design and detailing and deficient construction can lead to major structural failures, lower performance and occupant health problems related to the presence of fungi products. The wetting and drying processes of walls subjected to rain penetration is challenging to evaluate and to characterize since the amount of water involved, its location in the envelope, and the time it takes to dry are usually unknown.

An experimental program was developed with Concordia University and the industry (through an NSERC program) to document the performance of wall assemblies under specific climatic loadings including rain infiltration. For the purpose of this experimental program, the wall system components and the environmental conditions have been established based on Montreal's weather and common construction practices (see Table 1 for specimen details). The wetting load consisted in the insertion of a wetted bottom plate insert at the bottom of each wall (see Figure 4) at the beginning of each of the four

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imposed sets of climatic conditions, representing the months of August to November in Montreal. This wetting load procedure was based on previous work (St-Hilaire and Derome, 2005a,b, 2006). The main objective of this test was to document the behavior of different wall systems in which the bottom plate had been wetted by some rain infiltration.

METHODOLOGY AND EXPERIMENTAL SETUP

Description of Specimens

The construction of the wall specimens was typical of the residential wood-frame construction found in the Montreal region. Their composition consists of the following from the outside in:

- Exterior cladding
    - stucco on two layers of building paper or
    - wood cladding on furring and spun bonded polyolefin
- Exterior insulation sheathing
    - extruded polystyrene for 3 specimens only
- Sheathing
    - oriented-strand board (OSB) OR
    - plywood OR
    - asphalt-coated fiberboard
- 2” x 6” (38 mm x 140 mm) wood studs with glass fiber insulation
- Gypsum board
    - with polyethylene sheet OR
    - low-permeance paint

A set of 15 wall systems, as described in Table 1, was studied to cover all possible combinations.

The wall specimens were installed within a test hut which was built within an Environmental Chamber where the air temperature and relative humidity could be controlled.

Loading Conditions

Conditions during test preparation—pre-conditioning. The inside conditions of the environmental chamber and the inside of the test hut were set at 21ºC and 60% for some homogenization of the moisture content of the wood and wood-based components for a period of 3 weeks before the start of the test.

Table 1. Specimens’ Compositions

Panel No.	Interior Finish		Insulation Core	Sheathing Material				Cladding System	
	Polyethylene and Painted Gypsum	Painted Gypsum	38 × 140 mm @ 400 mm cc with Glass Fiber Batt Insulation	Oriented Strand Board (OSB)	Plywood (PW)	Fiberboard (FB)	Insulation Sheathing (Polystyrene)	Wood Siding on Furring and Spun Bonded Polyolefin	Cement Stucco on Metal Lath and Two Layers of Building Paper
17									
18									
19									
20									
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24									
25									
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27									
28									
29									
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31									

Exterior and interior conditions during test. For the exterior conditions, the goal was to reproduce the typical daily variations established from the averaged maximum and minimum conditions derived from weather data of over 30 years for the Montreal region (August through November). These conditions, shown in Table 2, were estimated using the selected moisture conditions of a 10% worst year in Montreal (Candanedo et al 2006) and the average Montreal weather data (Teasdale St-Hilaire 2006). For November, the air temperature and relative humidity were kept constant at 2°C and 80%.

The typical interior conditions values (temperature and RH) for the months of August through November were set as 21°C for the temperature (without variation) and 50% for the relative humidity. These conditions were set within the test hut while the exterior conditions were reproduced in the environmental chamber.

Wetting load—wetted bottom plate insert. During the four-month period of testing, the wetted bottom plate inserted at the bottom of each wall was replaced four times, i.e. each time the climatic conditions were changed. The bottom plate inserts were cut from longer pieces of lumber that had been immersed in water for 4 weeks. Each piece of lumber was sealed with paraffin wax on 3 sides: both ends and one wide surface (the surface to be seated in the wall).

Monitoring Procedure

The monitoring protocol combined electronic and gravimetric measurements. Thermocouples (TC), relative humidity sensors (RH), moisture content probes (MC), and gravimetric samples (SH) were located on the sheathing and in the studs as per Figure 1. The electronic and gravimetric monitoring grids were symmetrical along the central axis of each specimen to provide equivalent locations in the specimens for both types of readings.

Electronic monitoring. In terms of electronic equipment, the following sensors were installed in each wall specimen: 12 moisture content probes, 16 Type T thermocouples, and 2 relative humidity sensors. All the sensors and controls were linked to a Data Acquisition System (DAS). Readings were taken automatically every 10 minutes for the complete duration of the test.

Calibration of the thermocouples was done through a thermistor reading and verification with a steady-state homogeneous chamber temperature. Calibration of relative humidity sensors at the end of test was done using a dew-point hygrometer at two relative humidities. Calibration of moisture content probe readings was done using a gravimetric procedure for each wood-based material being monitored.

Gravimetric monitoring. The gravimetric analysis involved the regular weighing of sheathing and bottom plate insert samples during the test and their drying at the end of the test to determine their exact moisture content. Eighteen gravimetric sheathing samples (eleven of 2.8 cm and seven of 4.1 cm in diameter) were used in each wall. The wetted bottom plate inserts were monitored using the methodology described below. Figures 3 and 4 illustrate the gravimetric monitoring.

For the whole duration of the test, all gravimetric measurements for the sheathing and wetted inserts were made weekly (on the same day), including on the first day of each climatic period, for a total of four times per climatic period.

The sheathing gravimetric samples were removed, transported in vapor-tight and airtight bags, weighed, and then put back as quickly as possible. At the end of the test, the OSB and plywood samples were oven-dried at 97ºC while the fiberboard sheathing samples were oven-dried at 57ºC. All samples were then weighed one last time just after drying.

For the bottom plate inserts, a 1 cm thick piece was cut from one end. The cut face was waxed and the bottom plate insert put back into the wall with a dummy to replace the lost volume. The 1 cm portion was then used to determine the moisture content distribution across the bottom plate by cutting slices as follows (based on the method described in Tremblay et al, 2000):

1. A thin slice of one of the ends of the bottom plate insert is cut perpendicular to the wood grain to remove the wax. A 1 cm sample is then cut from that cut-off, always on the same side of the bottom plate insert.
2. The resulting 1 cm sample is first cut into three pieces (a, b and c). For seven walls, these three pieces are weighed and dried and the moisture content is calculated from these data. For the other eight walls, each of these a, b and c pieces is further sliced into twenty smaller pieces. The first fifteen slices are cut with a microtome; the remaining portion of wood is cut into five pieces with a blade, as shown in Figure 2. The sample ‘a’ is the part of the bottom plate that was facing the sheathing side; the ‘b’ piece is

Table 2. Exterior Conditions

	$T_{min\ mean}$, °C	T_{mean}, °C	$T_{max\ mean}$, °C	$RH_{mean\ at\ 6\ a.m.}$, %	RH_{mean}, %	$RH_{mean\ at\ 3\ p.m.}$, %
August	14.7	19.7	24.7	86	75	58
September	8.6	13.6	18.6	87	77	62
October	2	7	12	84	72	62
November	2	2	2	80	80	80

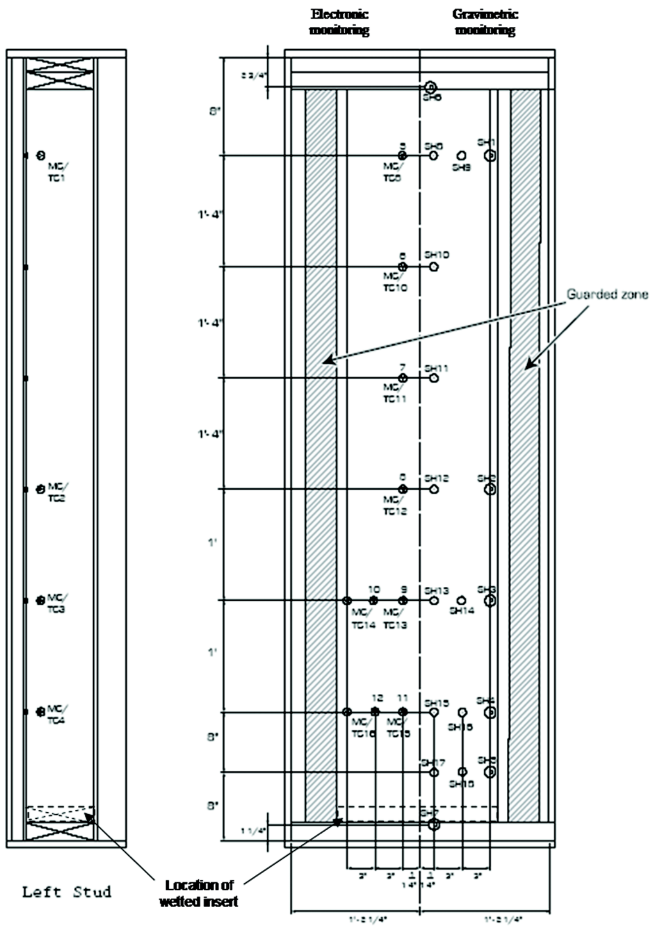

Figure 1 Location of electronic sensors and gravimetric samples (excluding RH sensors and pressure taps).

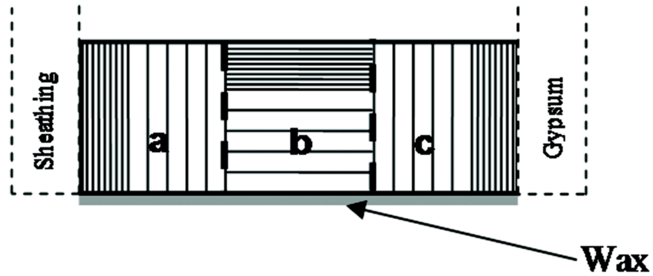

Figure 2 Slicing scheme for wetted bottom plate gravimetric samples, where parts A face the sheathing, parts B face the insulated cavity, and parts C face the gypsum.

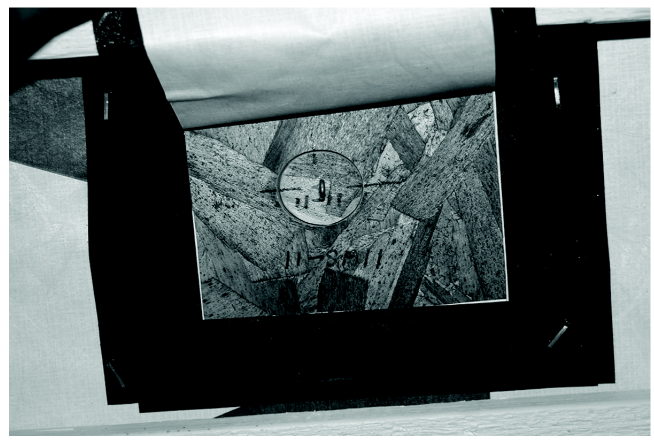

Figure 3 Example of sheathing gravimetry samples.

Figure 4 Wetted bottom plate inserts being inserted.

the central one while the sample ‘c’ is the one facing the gypsum. All slices cut with the microtome are 0.34 mm thick. The pieces cut with the blade are larger and their thickness is measured with an electronic caliper.

3. As soon as they are cut, the slices are weighed to provide the moisture gradient within the wetted bottom plate (weighing balance, precision ± 0.00001 g).
4. All the wood slices are oven dried at 97°C just after being weighed.

RESULTS

Graphs showing the variations in moisture content (mass of moisture per dry mass of wood) over the four climatic periods for the sheathing gravimetric samples were plotted for the 15 walls in which wetted bottom plate inserts were used for wetting. As examples, the weekly gravimetry results for Panels 19 and 20 are presented in Figures 5 and 6. These walls have the same sheathing material (plywood) and interior finish (polyethylene, painted gypsum board), but Panel 19 has a wood cladding while Panel 20 has a stucco cladding. For Panel 19 (shown in Figure 5), it can be seen that the gravimetry samples have a very similar behavior until the November period; although there is a slight increase in moisture content, all samples remain below 10% moisture content. During the

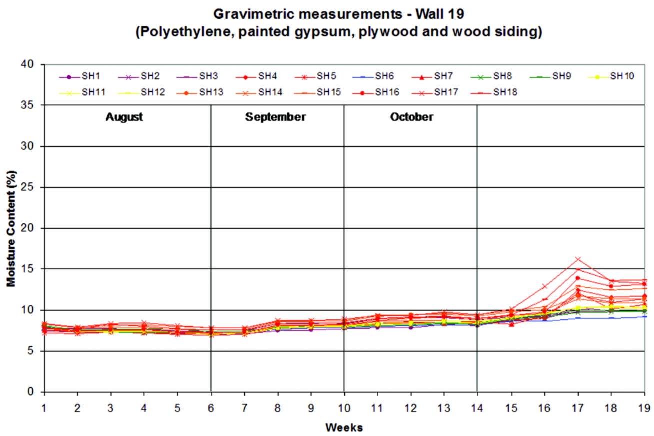

Figure 5 *Moisture content variations in gravimetric samples of Panel 19.* ***Note:*** *The rainbow color scheme for samples from the top of the wall (purple) to the bottom (red).*

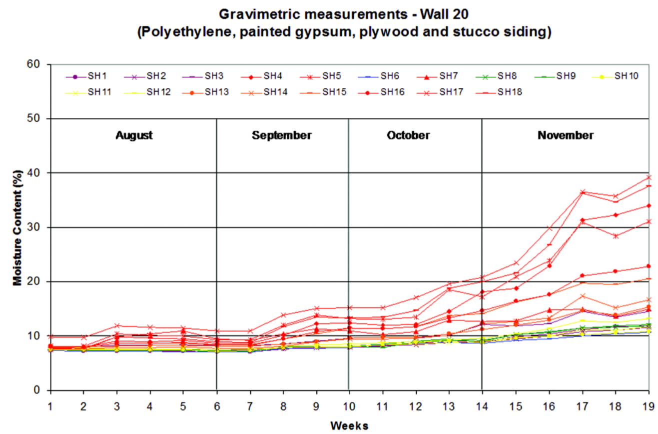

Figure 6 *Moisture content variations in gravimetric samples of Panel 20.*

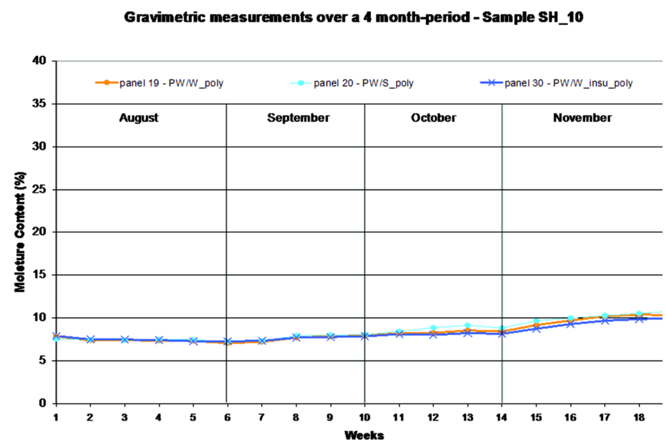

Figure 7 *Moisture content variation of gravimetric sample SH10 (Panels 19, 20, and 30).*

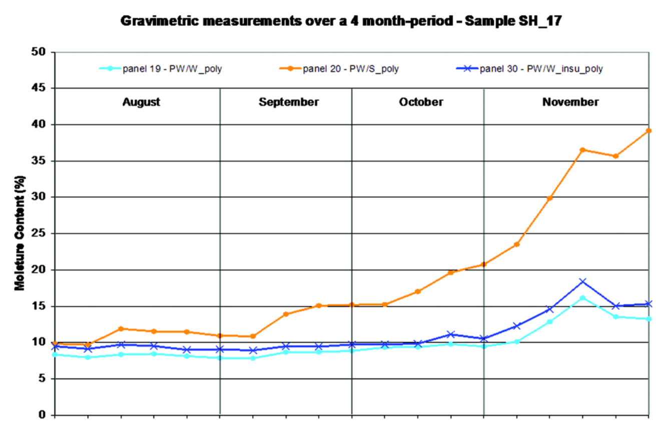

Figure 8 *Moisture content variation of gravimetric sample SH17 (Panels 19, 20, and 30).*

November conditions, the moisture contents increase somewhat faster, up to about 16% for sample SH17. There is some drying during the 4th week of the period. The samples that show higher moisture content increase (shown with red and orange lines in Figure 5) are those located at the bottom of the wall (i.e. SH4, SH5, SH7, SH13, SH14, SH15, SH16, SH17, and SH18). This was expected since the wetted bottom plate insert is in contact with the lower portion of the sheathing.

An overall increase in moisture content over the duration of the test can also be seen for Panel 20 (Figure 6). A spread of moisture content is noticeable from week 3 and continues to grow all along the test. The samples at the bottom (shown with red and orange lines in Figure 6) have a much more significant moisture accumulation than those at higher locations.

The data of the other panels show that the patterns seen and described for walls 19 and 20 are somewhat consistent for the 15 wall panels tested, i.e. that although there may be some drying in some specimens toward the end, there is an overall increase in moisture content (especially in the November period), the moisture content of the gravimetry samples in the lower portion of the sheathing have higher moisture contents than those in higher locations, the panels with a stucco cladding have a faster and more significant increase of moisture contents than those with a wood cladding, and the presence of the insulation sheathing appears to slightly increase moisture accumulation and reduce drying.

Graphs were also plotted to compare the change of moisture content at specific locations for all wall panels studied. Figures 7 and 8 compare the weekly variations in moisture content over a four-month period for two selected gravimetric samples. These samples were selected based on their location in the panel which shows how moisture variation can differ from top to bottom. Sample SH10 (Figure 7) is located in the upper portion of the sheathing while sample SH17 (Figure 8) is located next to the wetted bottom plate insert. Both graphs include only three walls for clarity purposes, i.e. walls 19, 20 and 30.

Sample SH10 (Figure 7) shows a slight moisture uptake for the first three periods of the test (weeks 1 through 14). The coldest conditions of November seem to have a higher impact on the moisture content variation, resulting in an increase followed by stabilization plate occurring in the last two weeks of the month. No return to initial moisture content levels was observed. The impact of the wetted bottom plate insertions at the beginning of each period is more significant for sample SH17, which is directly influenced by the insertion. Figure 8 shows the moisture variation induced by the monthly insertions and the impact of this moisture intake based on the composition of the wall, which was not so significant in Figure 7. The analysis reveals that most of the gravimetry samples located in the lower portion of the sheathing show a similar behavior.

To illustrate the moisture accumulation pattern at the end of testing, the average variation between the initial moisture content was calculated for each gravimetry monitoring position. The resulting average variation for each position, ranging between 4% and 12% moisture content, was plotted on the elevation of the wall specimens as shown in Figure 9. The darker regions at the bottom represent areas with higher moisture content variation. It can be seen that the closer the gravimetry specimens are to the wetted bottom plate insert, the more moisture they tend to retain. Although, the specific numbers vary for each panel, this pattern is found in all panels and is consistent with previous findings described above.

The moisture content distribution across the inserted bottom plate was evaluated on a weekly basis as described in the gravimetric procedure section. As mentioned, the sample taken from the wetted insert for the moisture evaluation was cut in 3 wood blocks (a, b and c) for seven walls while the other eight walls were studied using the slicing method, i.e. each of the 3 wood blocks were further cut into 20 slices. For those eight last walls, weekly moisture content results obtained from each wood slice have been plotted on three different graphs based on the wood block position (a, b or c). This allows visualization of the moisture loss that occurred over each period where the samples were weighed (week I through week IV). Figures 10 and 11 show the moisture movement in the wood block ‘a’ for two panels (17 and 18) during the August and the November periods. The wood block ‘a’ is the one facing the sheathing. The x-axis represents the position (mm) of the moisture content based on the slicing depth. The value at zero millimeters corresponds to the surface of the specimen while the last value is located at 46 mm (which corresponds approximately to the third of the bottom plate width from which block “a” was cut). Wall 29 (showed in Figure 12) was studied using 3 blocks (a, b and c), giving a more general overview of the moisture movement over the testing period.

These panels (17, 18 and 29) have been selected based on their composition. They have the same sheathing material and interior finish permeability. Panel 17 has a wood cladding while Panel 18 has a stucco cladding. Panel 29 is identical to

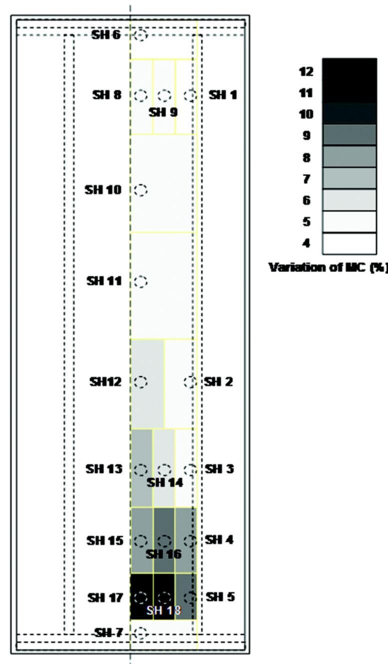

Figure 9 *Graphical representation of the distribution of average moisture content variations.*

Panel 17 with the addition of an insulation sheathing. For walls 17 and 18 (Figures 10 and 11), the moisture content gradients are quite pronounced at the first measurement (Week 1, top line in the graphs), ranging from above 40% at the surface to about 20% at 46 mm. We also see that for all three wall panels, there is less drying of the wetted bottom plate insert during the November conditions than during the August conditions. Panel 18 dries faster than Panel 17, but both dried to approximately the same level. For Panel 29, drying levels are slightly higher than the other two walls.

A more global method of comparison was also used. Based on the principle that problems may occur when the materials do not dry completely, the difference between the initial and final moisture contents of each gravimetry sample was calculated, corresponding to the moisture content variation over the test duration of the sample. For each wall, a weighted overall average variation was then calculated. The weighting factor applied to the variation of each gravimetry sample consisted of the ratio between the surface area of that gravimetry sample’s “zone” (refer to Figure 9) and the total area of sheathing being monitored with gravimetry (864 sq.in). This method allows an indication of the global performance of the wall specimen.

Table 3 shows the results for all wall panels, ranked from highest to lowest weighted average variation in moisture content, and synthesizes the main trends already identified with the moisture content graphs. This table clearly highlights the impact of the cladding type on moisture accumulation. All panels with the wood cladding have lower overall weighted

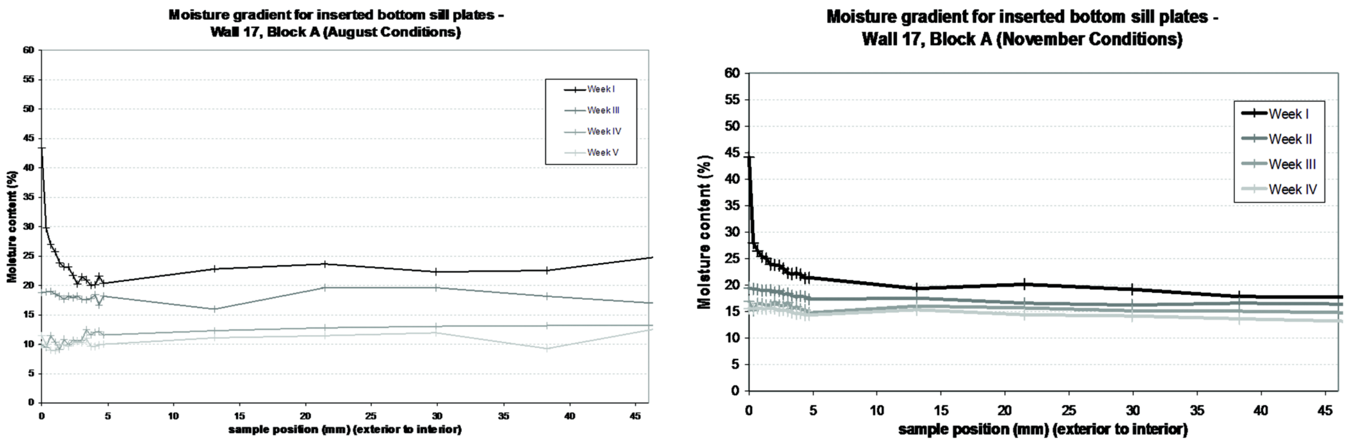

Figure 10 *Panel 17, wetted insert moisture content, August and November conditions.*

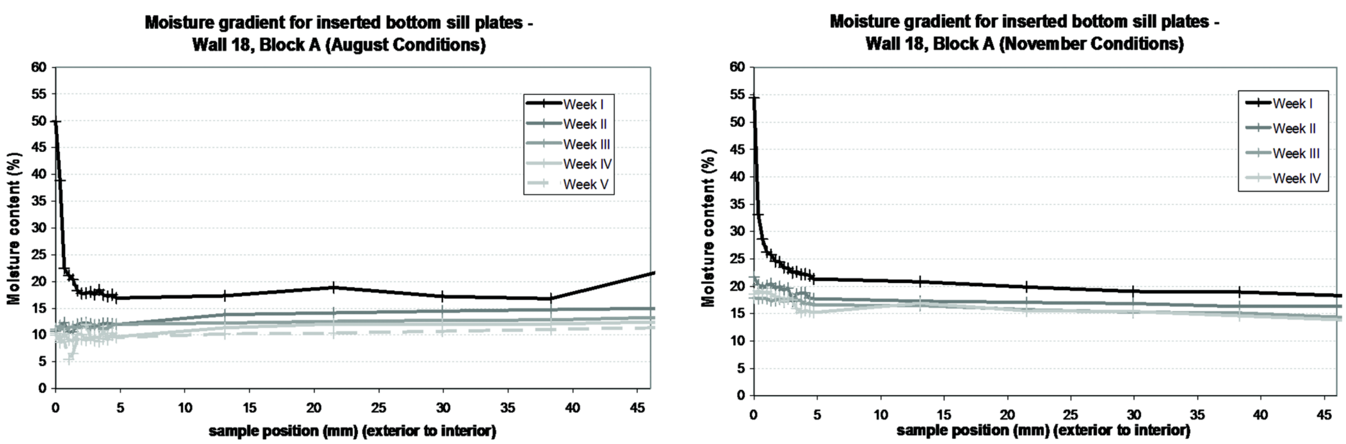

Figure 11 *Panel 18, wetted insert moisture content, August and November conditions.*

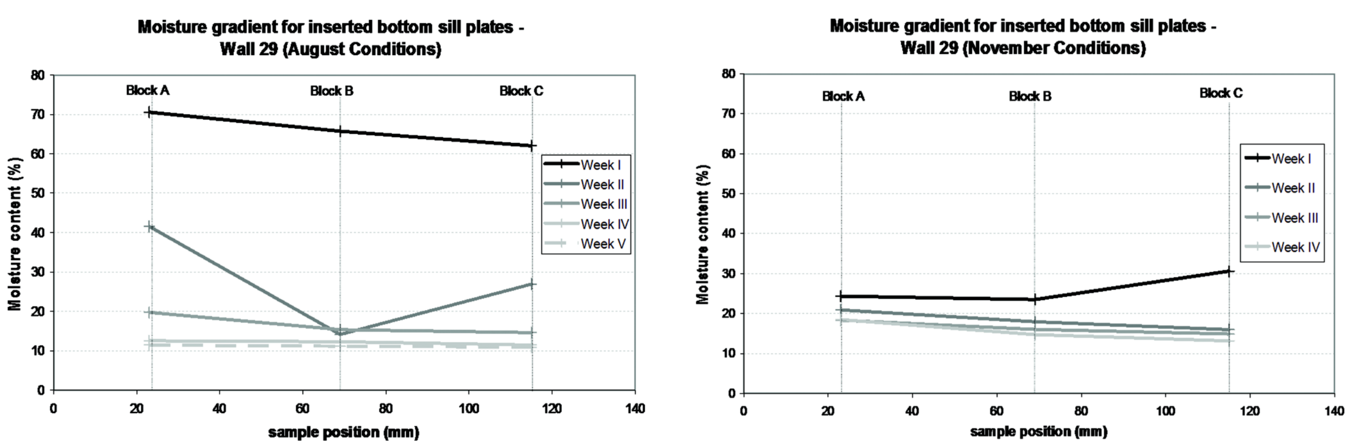

Figure 12 *Panel 29, wetted insert moisture content, August and November conditions.*

average moisture content variations than those with a stucco cladding. For the assemblies and conditions studied, the cladding type is the main parameter affecting moisture accumulation in the sheathing. It appears that the air space behind the wood cladding allows air to circulate and increases the drying ability of the sheathing.

However, the impacts of the other parameters, which are interdependent and not as significant, are not as easily

Table 3. Panels Composition and Moisture Content Variation

	Cladding		Rigid Insulation	Sheathing			Interior Finish		Weighted Average Variation, % M Per Dry Weight
	Stucco	Wood		OSB	PW	FB	Poly + Painted Gypsum	Painted Gypsum	
Panel 28									0.58
Panel 24									0.51
Panel 22									0.51
Panel 26									0.49
Panel 18									0.45
Panel 20									0.44
Panel 25									0.34
Panel 23									0.33
Panel 29									0.26
Panel 30									0.18
Panel 27									0.17
Panel 19									0.16
Panel 17									0.15
Panel 31									0.14
Panel 21									0.03

Table 4. Weighted Average Cariations in Moisture Content for Different Compositions

Wood + Rigid Insulation		Wood Cladding		Stucco Cladding		Vapor Barrier
Specimen No.	Averaged M Variation	Specimen No.	Averaged M Variation	Specimen No.	Averaged M Variation	
			OSB			
	0.26	#17	0.15	#18	0.45	With polystyrene
		#23	0.33	#24	0.51	paint
			Plywood			
#30	0.18	#19	0.16	#20	0.44	With polystyrene.
		#25	0.34	#26	0.49	paint
			Fiberboard			
#31	0.14	#21	0.03	#22	0.51	With polystyrene
		#27	0.17	#28	0.58	paint

assessed from Table 3. In Table 4, the weighted average variations in moisture content values are grouped according to the composition of the assemblies in order to detect the impact of various parameters.

Vapor Barrier

For all specimens with a wood cladding (#17, #23, #19, #25, #21, and #27), the presence of a polyethylene film resulted in lower weighted average moisture content variations. It seems that the polyethylene sufficiently retards diffusion of moisture from the test hut into the assembly, while the relatively permeable wood cladding allowed some drying toward the exterior. The opposite occurred for all specimens with a stucco cladding (#18, #24, #20, #26, #22, and #28). For those specimens, with a relatively impermeable cladding, the greater permeability of the paint allowed some drying toward the interior. The effect of the polyethylene film on moisture accumulation is more significant for specimens with a wood cladding than for those with a stucco cladding.

Extruded Polystyrene

Each specimen with rigid insulation retained slightly more moisture than its counterpart with no insulation (#29 vs. # 17, #30 vs. #19, and #31 vs. #21). This is most likely explained by the fact that the insulation sheathing is air- and vapor-tight, which reduces the ability of the sheathing to dry, although to a lesser degree than stucco without an air space.

Sheathing Material

It can be seen that the impact of the sheathing material on moisture accumulation varies depending on the type of cladding. For all specimens with a wood cladding, those with fiberboard sheathing have the lower values, and those with plywood sheathing have the higher values. For the specimens with stucco cladding, the opposite occurs. For the specimens with rigid insulation, it is the OSB that has the highest value. In all cases (excluding the specimens with rigid insulation), the values for the specimens with an OSB sheathing and those with a plywood sheathing are close, while the values for the specimens with a fiberboard sheathing have the greater spread among them. It can also be seen that the fiberboard sheathing is the material that absorbs the most moisture and also dries the most when given the opportunity: the specimens with the highest (#28) and lowest (#21) weighted average moisture variation have fiberboard sheathing.

CONCLUSIONS/RECOMMENDATIONS

Fifteen walls specimens were subjected to water insertion simulating rain infiltration and to specific climatic conditions representing the months of August to November for the Montreal region.

The results show a very consistent moisture accumulation pattern, with the moisture accumulation being highest closest to the wetted bottom plate insert, i.e. in the lower portion of the sheathing. The weighted average moisture content difference was used to give an idea of the overall performance of the specimens and to identify coherent trends relative to the impact of the various parameters on moisture accumulation. For the conditions studied, the parameter that had the most impact is the exterior cladding (wood with or stucco without an air space): the specimens with a stucco cladding reached higher moisture content levels and dried less than those with a wood cladding. The impacts of the interior finish vapor permeability, the presence of insulation sheathing, and the sheathing material are interrelated and relatively less significant than the impact of the type of cladding.

Further analysis with modeling is ongoing to determine more precisely the impact of each parameter studied and the significance of the results for a full year of climatic conditions.

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