FIELD TEST OF HYGROTHERMAL PERFORMANCE OF HIGHLY INSULATED WALL ASSEMBLIES

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ABSTRACT

Climate change has led to governments mandating greater energy efficiency in building codes throughout Canada and the US. Increased energy efficiency requires that building envelopes have thermal resistances beyond what is now achieved with traditional light wood framing and cavity insulation. This evolution of building assembly design may introduce unintended durability concerns.

To investigate potential durability issues, six types of high thermal resistance (High RSI) wall assemblies were constructed at the University of Waterloo Building Engineering Group's building envelope test facility (BEG Hut). This study compares the hygrothermal performance of conventional 38 x 140 mm framing with exterior insulation with three types of deep cavity framing – double stud, I-Joist stud or 38 x 184 mm wood framing. The wall assemblies had an average installed thermal resistance of RSI 6.8 and they were installed with both north and south-facing orientations to observe their relative performance.

The hygrothermal conditions of each wall including Relative Humidity, Moisture Content, Temperature and Heat flux were monitored under typical indoor conditions and climatic exposure. In addition, each wall was subjected to a simulated air leakage test performed during the winter. The moisture content of the oriented strand board sheathing and framing plates were measured via electric moisture sensors installed in the main wall cavity and used as the main durability performance indicator.

This paper presents the design, construction, and instrumentation of the High-RSI wall study as well as the hygrothermal performance of these High-RSI wood-frame walls with condensation, mould, and decay risk analysis. This project was part of the NSERC strategic research Network for Engineered Wood-based Buildings Systems (NEWBuildS). The results of this study will aid in the development of climate-sensitive design guidelines for High-RSI walls. This will help ensure that walls that comply with increasingly stringent building codes are durable.

INTRODUCTION

Building energy consumption accounts for approximately one third of Canada's greenhouse gas emissions, of which 15% are attributed to the residential sector (OEE, 2012). This sector also accounts for about 16% of Canada's total energy use. The energy efficiency requirements for buildings within national, provincial, and municipal building codes across Canada and the US have been rapidly changing in recent years to address this issue.

In Canada, an EnerGuide rating of 80 for "building enclosure only" is required to meet the energy efficiency design-criteria in both Ontario and British Columbia. Further, the mandate of 'net-zero ready' and carbon neutral construction for new residential housing by 2020 will require significant changes in the insulation levels within wood-frame building assemblies. The recently updated National Energy Code for Buildings

(NEBC 2011) requires an energy efficiency improvement of 26% over the requirements in the 1997 version. In the USA, higher energy efficiency requirements have also been included in the International Energy Conservation Code (IECC 2012) and both the International Residential Code (IRC) and the International Building Code (IBC).

To achieve these higher levels of energy efficiency, the anticipated effective RSI values of walls will need to be higher than the current Ontario Building Code (OBC) 2012 minimum thermal resistance levels RSI 3.9. The effective thermal resistance may need to be as high as RSI 7.0 for walls and RSI 10.6 or higher for roofs/attics depending on windows, HVAC systems and climate zones. These levels of insulation cannot be achieved with traditional light, wood framing (38x89mm, 38x140mm) using cavity insulation alone. The resulting changes to building design, material use and construction to accommodate increased energy efficiency may have unintended consequences on the long-term durability of wood-based structural materials. Consequently, it is important to provide the building industry with the science to determine the design and construction guidelines that will minimize the potential for building envelope failures related to non-traditional assemblies.

This paper presents the design, construction, and instrumentation of the High-RSI wall study as well as the hygrothermal performance of these High-RSI wood-frame walls with condensation, mould, and decay risk analysis.

EXPERIMENTAL SETUP

To investigate the risks associated with reduced drying capacity, thirteen test walls were built and inserted into the exterior walls of the BEG Hut during the months of July and August 2012. Of the six high RSI wall designs in this study, three investigated the relative performance of exterior insulation using traditional 38 x 140 mm framed walls with fibreglass cavity insulation. The types of exterior insulation used in these walls were polyisocyanurate (foil faced), extruded polystyrene, and mineral wool. The average installed thermal resistance of these three assemblies was RSI 6.0.

Two additional wall types were built to investigate the performance of the deep framing cavities filled with dense-pack cellulose insulation. These deep cavity walls were constructed with either a 286 mm cavity using double stud framing, or a 241 mm cavity using I-Joist stud framing. The thermal resistances of these walls were RSI 6.8 and RSI 5.8, respectively.

Two test panels of each of these five wall types were built and installed on north and south facing orientations in order to compare the effects of direct solar radiation on wall performance. A typical 38 x 140 mm framed wall with fibreglass cavity insulation (RSI 3.87) was also included as a reference datum for both the north and south facing wall assemblies. Finally, a third deep cavity wall was constructed with 38 x 184 mm framing and insulated with 152 mm of closed-cell polyurethane spray foam insulation (ccSPF). This wall had an installed thermal resistance of RSI 6.4 and was only installed with a south facing orientation because of space limitations at the BEG Hut.

The hygrothermal performance of each wall was assessed under typical indoor conditions and climatic exposure. In addition, each wall was subjected to an air injection test to simulate air leakage from February 19^{th}

to April 8th, 2013. The moisture contents of the oriented strand board (OSB) sheathing and the plates were used as the primary performance indicator of durability and drying potential.

Wall configurations and the test facility

The wall assemblies were identified and colour coded to facilitate analysis. The deep cavity walls and the datum wall were designated as north or south with a Type number as follows:

- Type 1 (S1, N1) – Double Stud with dense-packed cellulose
- Type 2 (S2, N2) – I-Joist Stud with dense-packed cellulose
- Type 3 (S3, N3) – 38x140 mm Datum with fibreglass cavity insulation
- Type 4 (S4) – 38x184 mm (Spray Foam)

The remaining three wall types were constructed using the Type 3 Datum framing as a base with fibreglass cavity insulation and configured with three different types of exterior insulation. These three wall assemblies were identified as:

- Type 5 (**S5, N5**) – 38x140 mm 50 mm (RSI 2.18) Polyisocyanurate
- Type 6 (**S6, N6**) – 38x140 mm 64 mm (RSI 2.21) Extruded Polystyrene
- Type 7 (**S7, N7**) – 38x140 mm 76 mm (RSI 2.11) Mineral Wool

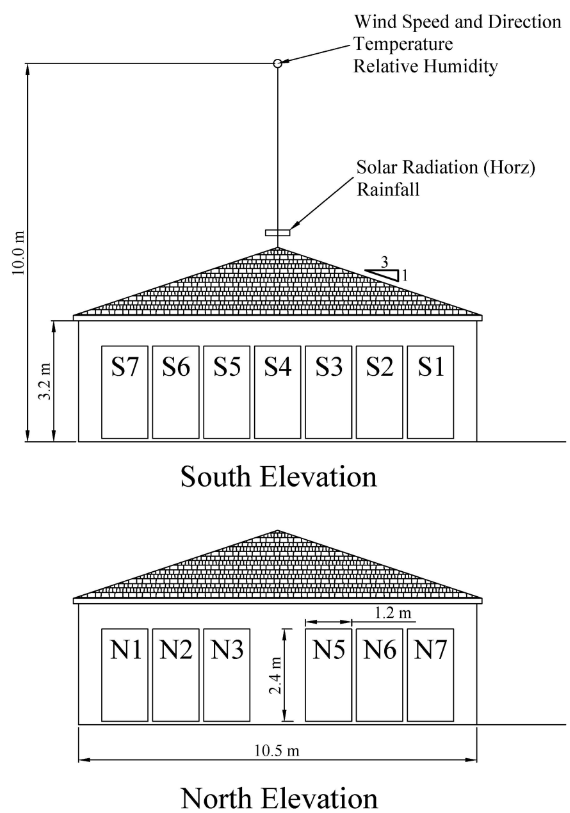

FIGURE 1: NORTH AND SOUTH ELEVATIONS OF THE BEG HUT FACILITY ILLUSTRATING THE SIZE OF THE BUILDING AND THE POSITIONING OF THE TEST PANELS.

The location of each test wall installed at the BEG Hut is shown in Figure 1. The BEG Hut test facility is a 10.5 m square building with each of its exterior walls aligned with one of the four principal directions.

The weather station installed at the BEG Hut facility collects the ambient exterior temperature, wind speed and direction as well as relative humidity from a height of 10 m above grade. Incident global solar radiation is measured with a pyranometer, which is located lower on the instrumentation mast at roof height (Figure 1) with the tipping-bucket rain gauge.

The rough openings of the BEG Hut were finished with 38 mm XPS insulation, 12.5 mm plywood and wrapped with self-adhering water proof membrane on the exterior edge. The plywood was fastened to the building posts, beams or floor curb through the insulation.

The test panels were hygrothermally isolated using 305 mm I-Joists placed vertically between the test panels. Each I-Joist web was filled with 12.5 mm thick XPS insulation to make the side of the I-Joist flush with the edge of the flange. Waterproof

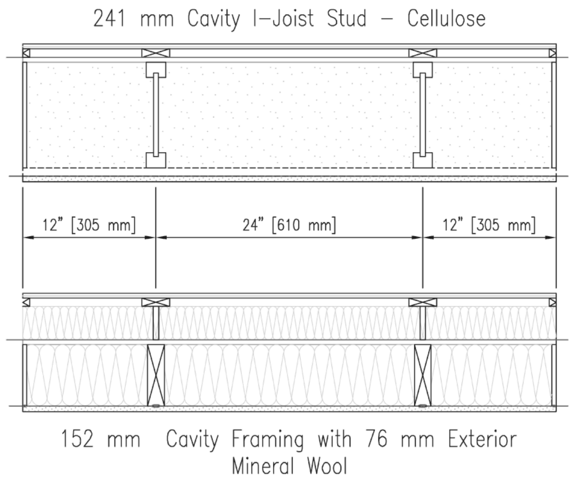

FIGURE 2: TYPICAL PLAN DIAGRAMS OF TEST PANEL FRAMING FOR THE TYPE 2 I JOIST (TOP) AND TYPE 7 EXTERIOR INSULATED (BOTTOM)

membrane was then wrapped around the exterior edge of the I-Joist. The openings were sized to allow for a 19 to 25 mm space around each test panel to accommodate the sensor wires and tubing as well as provide adequate space for the foam to penetrate the gap and make an air tight seal. The cross section diagrams shown in Figure 2 illustrate the typical framing plan of the deep cavity walls (Top – I Joist) and the exterior insulated walls (Bottom – mineral wool).

The test panels were framed on 600 mm centres with the overall dimensions of 1.22 m wide x 2.44 m high. Each wall assembly included double top plates. The framing was predominantly 38 mm thick SPF lumber with varying widths depending on the wall design. Table 1 summarizes the framing, insulation type(s) with the installed RSI value and vapour control details.

Water vapour control was provided by the 6-mil polyethylene layer in most of the walls; however, since walls should be able to dry in at least one direction, the interior 6-mil polyethylene was removed from the wall assemblies containing low vapour permeance exterior insulation. The extruded polystyrene (XPS) and polyisocyanurate had water vapour permeance values of 18 ng/Pa·s·m^2, and less than 1 ng/Pa·s·m^2, respectively, which precluded drying to the exterior. The 152 mm of ccSPF also did not require an additional vapour barrier.

The test panels were designed to isolate the central 610 mm wide cavity by using two 305 mm side cavities

Wall ID	Wall framing*	Insulation	RSI	6-mil VR***
S1, N1	140mm ext. framing; 89mm int. framing	286 mm cavity with dense pack cellulose	6.8	Yes
S2,N2	241 mm I-Joist stud; 241 mm plates	241 mm cavity with dense pack cellulose	5.8	Yes
S3,N3	140 mm framing	140 mm fibreglass insulation	3.9	Yes
S4	184 mm framing	152 mm closed cell spray polyurethane foam (ccSPF)	6.4	No
S5,N5	140 mm framing	140 mm fibreglass insulation; 50 mm PI	6.1	No
S6,N6	140 mm framing	140 mm fibreglass insulation; 64 mm XPS	6.1	No
S7,N7	140 mm framing	140 mm fibreglass insulation; 76 mm mineral wool	6.0	Yes

*All framing using 38 mm thick Spruce-Pine-Fir (SPF) lumber; studs are installed 600 mm OC with two nominal 300 mm side cavities for total frame width of 1.22 m. Wall framing includes single bottom and double top plate except the single interior frame top plate in walls S1 and N1.

**6-mil vapour retarder (VR) indicates the use of 6-mil polyethylene in the assembly.

TABLE 1: SUMMARY OF FRAMING, INSULATION TYPE(S), INSTALLED RSI VALUE AND VAPOUR CONTROL DETAILS

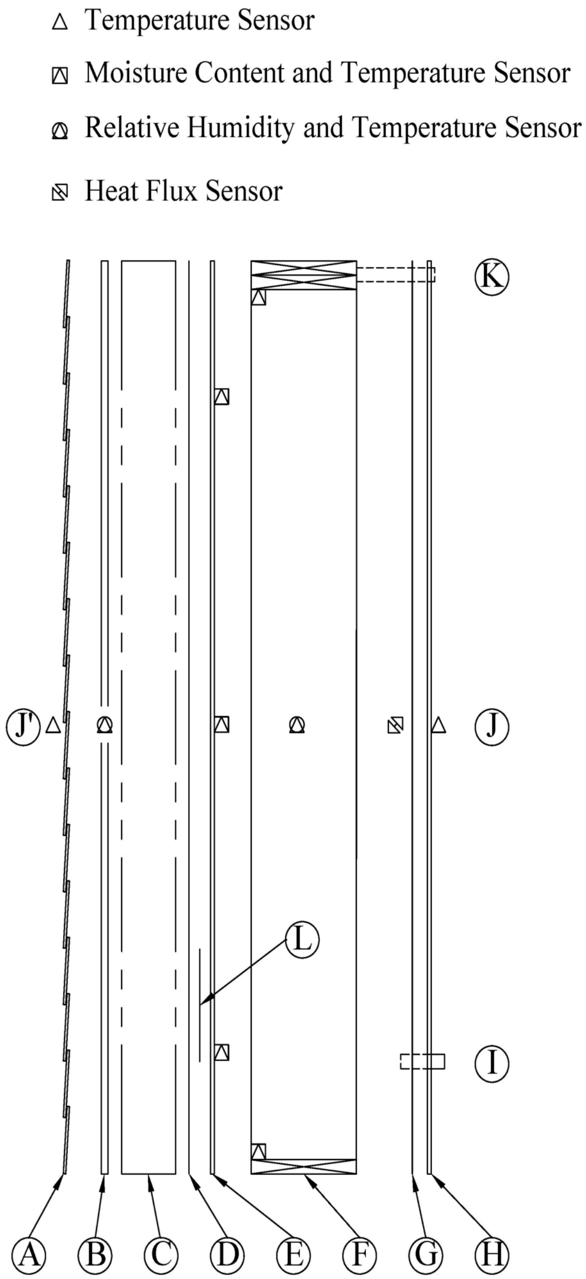

FIGURE 3: EXPLODED CROSS SECTION OF TYPICAL WALL ASSEMBLY. WALL COMPONENTS ARE IDENTIFIED ALPHABETICALLY AND LISTED IN THE ACCOMPANYING TABLE. PLEASE REFER TO TABLE 2.

ID	Wall component
A	11 mm Fibre cement siding
B	19 mm strapping / drainage space
C	Exterior Insulation (if installed)
D	SBPO air barrier and water resistive layer
E	11 mm OSB Sheathing
F	140, 184 or 241 mm framing as required
G	6-mil polyethylene (if installed)
H	12.5 mm drywall
I	Air injection port
J'-J	Sensors through wall insulation cavity
K	Air exhaust port
L	Exterior water injection wetting sheet

TABLE 2: WALL COMPONENT DETAILS FROM FIGURE 3

that provided hygrothermal buffering for the central cavity. To this end, the two outermost studs were framed using 9.5 mm plywood in order to maintain proportional thermal performance. In addition, each wall assembly was also designed with common control layers to facilitate comparison between the wall types. These assembly components were the exterior drained-screened wall system, 11.1 mm OSB sheathing, 12.5 mm interior drywall, and two coats of latex paint.

Instrumentation and monitoring

The High-RSI test panels installed in the north and south facing walls of the BEG Hut test facility were designed to hygrothermally isolate one framing cavity in the centre of each panel. This central stud cavity was monitored using temperature, relative humidity (RH) and moisture content (MC) sensors to determine each wall's response to environmental and simulated moisture loads. The MC-sensors were installed in the wood-based framing and sheathing components, while the RH-sensors were installed in the centre of the framing cavity and the exterior drainage space. Temperature sensors were placed with each MC-sensor and RH-sensors as well as on the interior and exterior surfaces of each test panel. The RH/T-sensors were used to determine vapour pressure differentials across the assembly components.The exploded cross section shown in Figure 3 displays the sensor locations relative to each wall layer as installed in the test panels. The wall components identified in Figure 3 are listed in Table 2.

The centralized data acquisition unit (DAU) installed at the BEG Hut was configured with five Campbell Scientific AM16-32B multiplexers (MUX), a main CR 1000 data logger and a 12 volt backup battery. Each test panel had 9 temperature, 2 relative humidity and 5 moisture content sensors installed. Data was acquired every 15 minutes and averaged hourly.

Temperatures were determined using precision 10k Ohm thermistors wired in series with a 1000 Ohm fixed resistor. These sensors had an accuracy of ±0.2°C at 25° C. These sensors were installed with each relative humidity, moisture content, and heat flux sensor as well as on the interior and exterior surfaces of the assemblies.

The relative humidity (RH) sensors used in this study were Honeywell model HIH-3610-004. Each RH-sensor was bundled with a temperature sensor and wrapped with spun-bonded polyolefin for protection against liquid water. These sensor bundles were mounted mid-depth in both the central stud cavity and the exterior drainage space. They were secured with nylon line and building tape to maintain their positioning while the insulation was installed. The HIH-3610 sensors had an accuracy of ± 2% RH from 0 to 100% RH under non-condensing conditions.

Electrical moisture sensors were used to monitor the moisture content of the OSB sheathing and the SPF framing. These MC-sensors were installed to a depth of 5 mm in the OSB sheathing and framing. The framing plate MC-sensors were installed 9.5 mm from the exterior edge of the framing. The OSB MC-sensors were located at elevations of 285, 1200, and 2040 mm along the vertical centreline of the central cavity as measured from the top of the bottom plate as shown in Figure 3.

TEST RESULTS AND DISCUSSION

The data collected during the High-RSI wall study were evaluated based on wall type and orientation through three distinct study intervals:

1. A fall/winter baseline period from November to mid-February,
2. A wintertime air leakage test from mid-February to early April, and
3. A springtime drying period extending from early April to early June

The variability of vapour pressure across each test assembly in response to climatic conditions was monitored and its effect on the moisture content of the OSB sheathing was evaluated over these three analysis periods. Each wall assembly was also compared between wall types, orientation as well as with the relevant datum wall.

The baseline analysis indicated that generally, the walls had very little vertical variation in sheathing moisture content with the exception of the cellulose insulated walls S1, N1 and N2.The only cellulose insulated wall that did not exhibit any vertical OSB MC variations was the south facing I-Joist wall, S2. Table 3 shows the average standard deviation between the three OSB MC-sensor datasets for each test panel. These data indicate that during the baseline period, the vertical moisture content profile generally varied less than 0.5% MC within the test panels. The cellulose-insulated walls, however, had much higher moisture variability within the OSB sheathing of the north facing I-Joist wall (N2) and the south facing double stud wall (S1).

Std. Dev	S1	S2	S3	S4	S5	S6	S7	N1	N2	N3	N5	N6	N7
Baseline	2.5	0.2	0.0	0.1	0.4	0.3	0.0	0.7	2.9	0.2	0.3	0.2	0.0
Air Leak	0.9	2.2	0.8	0.1	1.2	1.0	0.5	3.7	2.2	4.0	1.1	2.0	1.0
Drying	0.8	0.8	0.0	0.1	0.5	0.5	0.1	2.7	0.6	1.7	0.3	0.4	0.1

TABLE 3: VERTICAL VARIATIONS IN THE OSB MC-DATA ARE REPRESENTED BY THE STANDARD DEVIATION BETWEEN THE AVERAGES OF THE LOWER, MIDDLE AND UPPER OSB MC-SENSOR DATA DURING EACH ANALYSIS PERIOD.

The standard deviation data from the air leakage and drying periods show that the large deviations that occurred in S1 and N2 were reduced to less than 1% by the end of these periods. In contrast, the standard deviation of the vertical moisture profiles increased during the air injection test in walls N1 (Double Stud) and N3 (Datum). The lower standard deviation in the OSB MC-datasets of the N2 (I Joist) wall resulted primarily from the significant increase in the lower OSB MC during the air injection test (Figure 4 – Top)

The vertical OSB MC-profiles of the best and worst performing north facing test panels are shown in Figure 4 relative to the north datum (N3). The wide separation between the OSB MC-data recorded in the N2 wall during the baseline period contrasts with the uniform OSB MC-data measured in the test panels N3 (Datum) and N7 (Exterior insulated Mineral wool).

The moisture introduced by the injected air disproportionately increased the OSB MC-values measured at the lower or middle sensor locations, while the upper OSB MC-data were generally unchanged by the

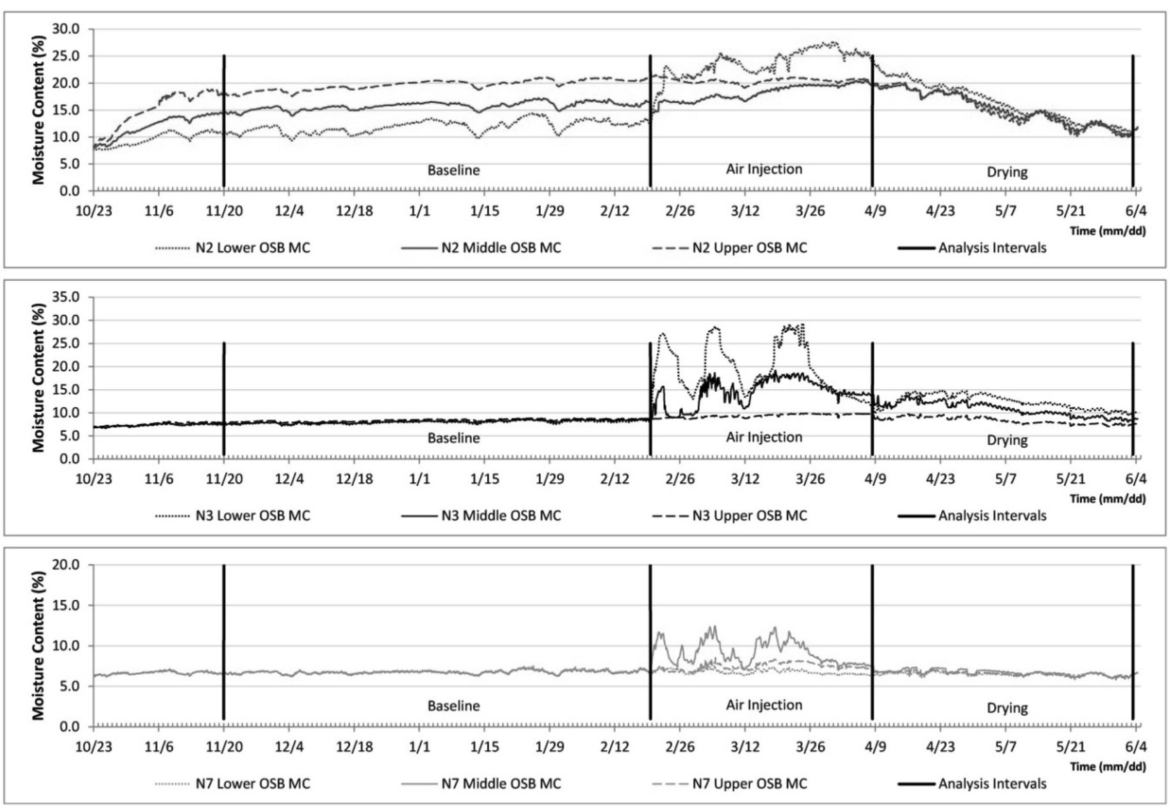

FIGURE 4: VERTICAL OSB MC-PROFILES FOR TEST WALLS N2 (TOP), N3 (MIDDLE), AND N7 (BOTTOM)

injected air. The effects of the injected air were most pronounced in the lower OSB MC-data of the deep cavity cellulose walls and the middle OSB MC-data of the exterior insulated walls. The exterior insulation of wall Types 5-7 increased the sheathing temperature at the lower OSB MC-sensor location, which suppressed the OSB MC-values. The middle and upper OSB temperatures were less affected by the heat of the injected air in these walls, which consequently led to higher mid-height OSB MC-values in the exterior insulated walls.

The data shown in Figure 4 also illustrate the different OSB MC responses of these wall types during the simulated air leakage test and drying periods. The lower OSB MC-data of N3 and N2 responded immediately to the injected air with the highest magnitude of the three intra-wall OSB sensors. The OSB MC-data for N7 (exterior insulated with mineral wool) shows that the initial and highest response to the injected air occurred at the mid-height OSB MC sensor. The best performing north facing wall was the exterior insulated wall N7 where the highest observed OSB MC was only 12.5% during the air leakage test. The vapour permeable mineral wool used in wall Type 7 allowed these walls to dry to the exterior.

The highest magnitude MC changes occurred in the OSB sheathing of the N3 datum and N2 walls. The shallow stud-cavity of N3 with its non-hygroscopic cavity insulation allowed the OSB MC to respond immediately to changes in temperature and vapour pressure. Three distinct cold weather 'drying' periods were clearly observed in the N3 OSB MC-data during the air leakage test. The best performing of the cellulose insulated deep cavity walls was the south facing I-Joist wall. The OSB MC-data from this wall is shown in Figure 5.

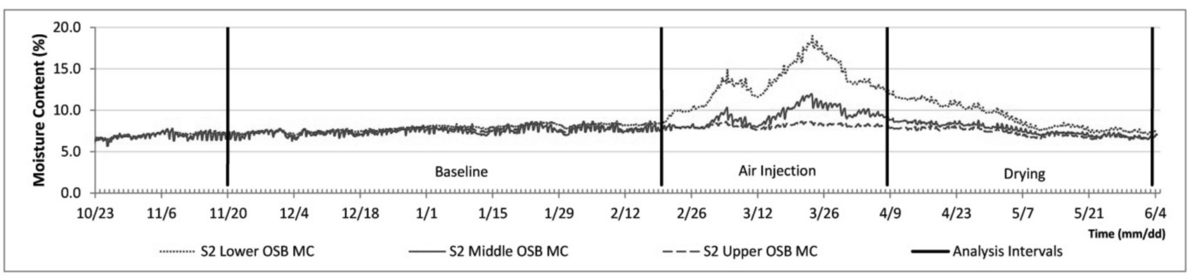

FIGURE 5: VERTICAL OSB MC-PROFILE OF THE SOUTH I-JOIST TEST WALL S2 DURING EACH OF THE ANALYSIS PERIODS

Condensation, mould growth and decay

High humidity levels and condensation within wall assemblies promote the growth of mould on wood-based components. As the moisture content of wood-based materials increases above the fibre saturation point (~28-30% MC), serious wood decay begins. However, once decay is initiated, it may continue until moisture content levels fall below 20% MC (Morris and Winandy, 2002). The results of the condensation analysis are presented in Figure 6. These data represent the total number of at-risk hours observed in each of the test panels during the study period from Nov 20, 2012 to June 3, 2013. The cellulose insulated deep cavity walls had the most potential condensation hours and the sheathing within these walls was most at risk. The exterior insulated walls had a minimal number of at-risk hours that predominantly resulted from the air injection test. The threshold used to determine mould growth risk was the combined criteria of surface moisture content greater than 16% MC (as recorded by the MC-sensors) and temperatures higher than +5°C.

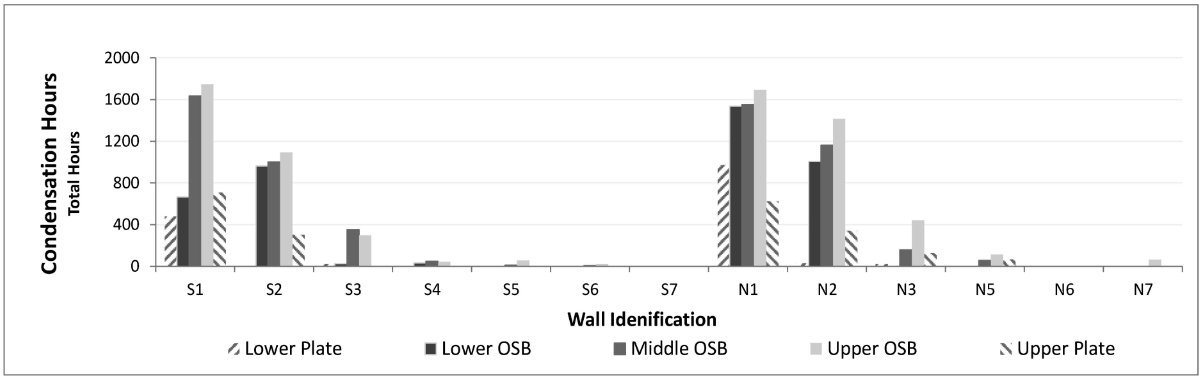

FIGURE 6: TOTAL POTENTIAL CONDENSATION HOURS IN THE HIGH-RSI WALL ASSEMBLIES FROM NOV 20, 2012 TO JUNE 3, 2013

The number of hours that each test panel exceeded these conditions was calculated and the totals for each of the MC-sensors are presented in Figure 7. These data show that the greatest mould growth risk occurred in the north facing deep cavity walls and the datum wall with the majority of the potential mould growth hours arising from the air leakage test. The relative humidity was calculated for each of these components by determining their partial vapour pressures from the stud cavity RH-data and the temperature data associated with each MC-sensor.

Decay risk hours			
S1	**N1**	**N2**	**N3**
1327	3027	2828	267
27.6%	**63.1%**	**58.9%**	**5.6%**

TABLE 4: TOTAL DECAY RISK HOURS FOR THE BOTTOM PLATES OF S1, N1, N2, AND N3 FROM NOV 24, 2012 TO JUNE 3, 2013

The only wall component to exceed the decay criterion was the lower plate in walls S1, N1, N2, and N3. The decay risk of these lower plates is summarized in Table 4 as the total at-risk hours and the percentage of time that the plates were at-risk during the study period. These data indicate that the most significant risk occurred in the north facing walls insulated with cellulose and specifically the Type 1 Double stud wall, which was the only south facing wall to have any decay risk. The decay risk was primarily associated with the air injection test and the extended drying times associated with the deep-cavity walls. The elevated moisture content in these lower plates was also likely adversely affected by the pooling of condensation that originated on the interior side of the OSB sheathing.

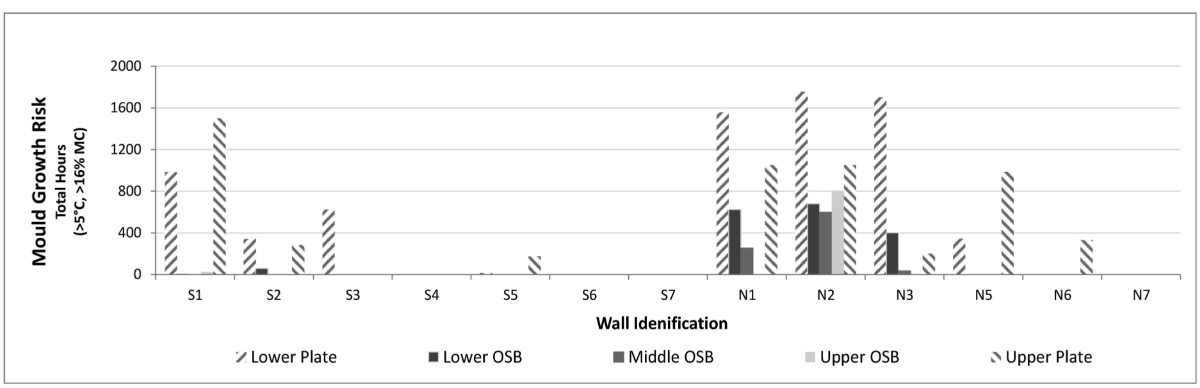

FIGURE 7: TOTAL MOULD GROWTH HOURS (>5°C, >16% MC) FROM NOV 20, 2012 TO JUNE 3, 2013

CONCLUSIONS

Thirteen high RSI walls with different insulation strategies were tested in a Building Envelope Test Facility under the Southern Ontario climate over one year. The hygrothermal performance of these test walls were analyzed under three periods: a baseline from Nov 20, 2012 to Feb 19, 2013, an air injection from Feb19, 2013 to April 8, 2013 and a drying period from April 8, 2013 to June 3, 2013. The main findings from the experimental results include:

- The air injection test illustrated that the warmer OSB sheathing of the exterior insulated walls reduced the risk of moisture related problems especially near the location of the air leak. The sheathing in wall Types 5-7 performed very well during the air injection test as the OSB MC-data were consistently below 16%.
- The upper section of the stud cavity and the upper framing members had very slight risks of mould growth in the walls with low vapour permeability exterior insulation (Types 5 and 6). The upper plate in wall Type 5 was the highest of the exterior insulated group with the moisture content of the N5 upper plate exceeding 20% for two weeks in March 2013.
- The vapour permeable exterior mineral wool (N7) performed the best out of all of the High RSI walls. The ability of the Type 7 walls to dry to the exterior kept the OSB MC below 8% during the baseline period and below 12% during the air leakage test.
- The deep-cavity cellulose-insulated walls had the highest moisture content levels in both the framing plates and OSB sheathing throughout the duration of the study period. These walls also had the highest number of condensation hours. The OSB MC-sensor data also indicated that the moisture content within the cellulose walls was non-uniform. The deep-cavity cellulose walls were also slower to dry in comparison with the exterior insulated walls.

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REFERENCES

Ontario Ministry of Municipal Affairs and Housing. 2006. Ontario Building Code. Online resource. Toronto: Orderline.com.

NRC IRC. 2011 National Energy Code of Canada for Buildings. Ottawa, On: Government of Canada

NRC IRC. 2010. National Building Code of Canada. 13th Ed. Ottawa:NRCC

Office of Energy Efficiency. 2012. Improving energy performance in Canada. Ottawa, Ont.: Natural Resources Canada. Retrieved from http://oee.nrcan.gc.ca/publications/infosource/home /index.cfm

Morris, P.I., Winandy, J.E. (2002). Limiting Conditions for Decay in Wood Systems. 33rd Annual meeting of the international research group on wood preservation, IRG/WP 02-10421, May: Cardiff, South Wales UK.