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TESTING R22+WOOD-FRAME WALLS FOR HYGROTHERMAL PERFORMANCE IN THE VANCOUVER CLIMATE: FIELD WALL PERFORMANCE

Project Number: 301013124 R22 Wall Testing

ACKNOWLEDGEMENTS
Funding was received from FPInnovations members, BC Housing, Forestry Innovation Investment, and ROCKWOOL™.

Mr. Mark Gauvin shared knowledge and experience from his previous test hut work. Input was received from BC Housing, the City of Vancouver, RDH Building Science Inc., Morrison Hershfield, and Mr. Richard Kadulski regarding the test plan of this study. BC Housing, ROCKWOOL, and RDH also reviewed this report. Assistance was received from SMT for instrumentation. A few companies provided materials. Conroy Lum provided great assistance in processing the data, in addition to reviewing this report.

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EXECUTIVE SUMMARY

This new study aims to generate hygrothermal, particularly moisture-related performance data for light wood-frame walls meeting the R22 effective (RSI 3.85) requirement for buildings up to six storeys in the City of Vancouver. The overarching goal is to identify and develop durable exterior wood-frame walls to assist in the design and construction of energy efficient buildings across the country. Twelve test wall panels in six types of wall assemblies are assessed in this study. The wall panels, each measuring 4 ft. (1200 mm) wide and 8 ft. (2400 mm) tall, form portions of the exterior walls of a test hut located in the rear yard of FPInnovations' Vancouver laboratory. This report, second in a series on this study, documents the performance of these wall assemblies based on the data collected over 19 months' period from October 2018 to May 2020, covering two winter seasons and one summer.

These six types of wall assemblies consist of different insulation strategies and materials, each with effective thermal resistance just exceeding R22, taking into account the thermal bridging caused by structural framing. Wall assembly No. 1 is framed with nominal 2 in. by 8 in. (38 mm by 184 mm) dimension lumber, with the stud cavities filled with nominal R28 glass fibre batt insulation. No. 2 is built with double studs (nominal 2 in. by 4 in. (38 mm by 89 mm) dimension lumber), placed at the same spacing along the interior and exterior wall faces but with a ¼ in. (6 mm) gap between the two studs and has the entire wall cavities filled with a highly vapour-permeable, 0.5-pcf (8 kg/m^3) open-cell spray foam (ocSPF). These two deep-stud walls, albeit with different insulation types, are expected to be similar hygrothermally, except for the impact of the different interior vapour control methods described below. Wall assemblies No. 3 to No. 6 are all split-insulated assemblies, each framed with nominal 2 in. by 6 in. (38 mm by 140 mm) dimension lumber and having the same interior insulation (R19 compressed from nominal R20 glass fibre batt insulation) in the stud cavities. The exterior insulations applied to the four walls are rigid stone wool (1.5 in. (38 mm) thick, in wall No. 3), extruded polystyrene (XPS, 1 in. (25 mm) thick, in No. 4), foil faced-polyisocyanurate (polyiso, 1 in. (25 mm) thick, in wall No. 5), and expanded polystyrene (EPS, 1.5 in. (38 mm) thick, in No. 6). The vapour permeance of these exterior insulation boards decreases from the stone wool, EPS, XPS, to the foil faced-polyiso insulation.

The vapour diffusion control layer of each wall is designed based on the insulation material(s) used and the common construction practices for the selected materials. Wall No. 2 initially has a vapour-retarding paint applied on the interior surface of the spray foam and has another vapour-retarding paint applied on the drywall before the start of the second winter (in late November 2019). Wall No. 5 has a vapour-retarding paint applied on its drywall from the beginning. The remaining wall assemblies all use sheet polyethylene (6 mil (0.15 mm) thick), a traditional interior vapour barrier installed between the wall studs and the drywall. One replicate of the walls labelled from No. 1 to No. 5 is installed north-facing, while a second replicate is installed south-facing. Wall No. 3 and No. 6 are installed to face east, with wall No. 3 serving as a reference wall for these three orientations (north, south, and east). All walls are sheathed with oriented strand board (OSB) structural sheathing and covered with a common synthetic spun-bonded polyolefin sheathing membrane to reduce the variables of testing. The effect of air leakage on moisture performance is not dealt with in this study, as all wall panels are built with both the inner and outer layers of the stud cavities to be airtight into sealed openings without any penetrations. No airtightness testing is conducted.

This study focuses on measuring the moisture content (MC) of wood (OSB, wall studs), the ambient environmental conditions including temperature and relative humidity (RH), and the corresponding vapour pressure gradients through each wall panel using sensors. Moisture loads, in the form of vapour (i.e., from the relatively high indoor humidity, around 50% RH maintained by a humidifier to simulate the conditions in a residential building) and liquid water (simulated by injecting water through a tube into a wetting pad built into the wall) are used to stress the walls for investigating their moisture-related behaviour. Wall performance discussions in this report focus primarily on the OSB sheathing, the same in each assembly, as it is the most sensitive component to moisture accumulation.

The following are general observations and conclusions:

- The test method has proved to be efficient for assessing the hygrothermal performance of exterior wall assemblies, providing meaningful data for assessing the relative performance of different wall assemblies.
- The measured temperature and RH from the test walls' ventilated rainscreen cavities, which are defined in this report as a simplified exterior boundary for comparing wall performance, well reflect the coastal climate of Vancouver, with the winter being mild and damp and the summer being warm and much drier.
- Among the three orientations (north, south, and east) covered in this test, the south-facing walls are warmer and drier than their north-facing counterparts, with the east between the north and the south, due to different solar effects.
- Consistent results are obtained from measuring the service environmental conditions, the moisture content of OSB sheathing, and using the measurements to assess potential vapour diffusion in these test walls.
- Related to wall design, the split-insulated walls have warmer OSB sheathing and it is much less likely for the sheathing temperature to fall below the dew point of the indoor air, compared to the walls without exterior insulation. When exterior insulation is used, there are negligible differences in the sheathing temperatures among the different insulation types, i.e., the type has little impact on the capacity to keep the sheathing warm when the rated R-values are approximately the same. However, the vapour permeance of the exterior insulation affects the wall's drying performance; vapour-permeable exterior insulation allows drying towards the exterior.
- The interior vapour control of the building envelope remains important for Vancouver's mild climate in humid residential buildings (e.g., with RH of around 50% during wintertime). The poly vapour barrier used in walls No. 1, No. 3, and No. 4 appears to be effective in minimizing outward vapour diffusion and the related wetting. For wall assemblies No. 2 or No. 5, the use of an interior vapour-retarding paint coupled with the wall's drying capacity does not sufficiently protect each wall from wetting caused by outward migration of indoor humidity for the indoor conditions, wall configurations and materials tested here. Further research is to be carried out.
- None of the test wall panels' OSB sheathing shows visible mould growth resulting from outbound vapour diffusion, although the mould prediction based on the Mould Index (MI) following the standard ASHRAE 160 and assuming the OSB sheathing falls into the "Very Sensitive" class suggests that test wall panels N2 and N5 should have shown mould growth by the end of the test. Wall assembly No. 5 with exterior foil faced-polyiso insulation including both wall panels N5 (north-facing) and S5 (south-facing) shows mould growth on the exterior surface of its OSB sheathing in and around the wetting pad, suggesting poor drying after water injection.

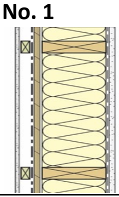
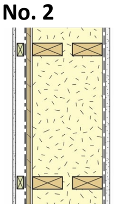
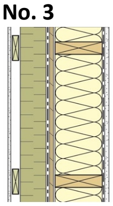
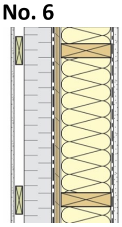
Given the importance of ensuring that there is adequate vapour diffusion, more detailed results of the study are summarized below starting with the two deep-stud wall assemblies No. 1 and No. 2, followed by the four split-insulated wall assemblies (from No. 3, No. 6, No. 4, to No. 5) in order of increasingly reduced vapour permeance of the exterior insulation used. The performance is primarily based on the data collected from the north-facing test wall panels N1-N5 for the wall assemblies from No. 1 to No. 5 and the east-facing test wall panel E2 for wall assembly No. 6, since the south-facing walls are drier than their north-facing or east-facing counterparts. The table below provides a concise summary and comparison for these six wall assemblies.

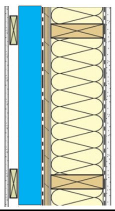
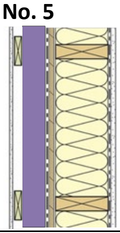
- For the deep-stud wall assembly No. 1, which is built with nominal 2 in. by 8 in. wood framing with an interior poly vapour barrier, the measured RH from the interior surface of its OSB sheathing remains below 80% over both winter seasons during the test; the measured MC at its mid-depth stays below 16% even after water injection. This wall can dry towards the exterior quickly. The test shows this wall should not have a large durability concern in the Vancouver climate, provided it is constructed airtight.
- For the deep-stud (double 2 in. by 4 in. studs) wall assembly No. 2, with ocSPF together with a vapour-retarding paint initially applied on the interior surface of the foam, and another coating of vapour-retarding paint applied on its drywall before the start of the second winter, the measured RH from the interior surface of its OSB sheathing stays above 90% over the first winter and decreases to below 90% but still well above 80% over the second winter. The test results indicate this wall's OSB sheathing is susceptible to mould growth, which is confirmed with the ASHRAE 160 standard MI value which exceeds 3.0 during the test period, when it is assumed the OSB sheathing falls into the "Very Sensitive" class. The MC measurements from its OSB sheathing indicates moisture accumulation during the winter. However, the wall shows good drying capacity, with drying towards both interior and exterior possible when conditions permit. Use of spray foam typically improves airtightness, which can reduce vapour condensation potential caused by air leakage. Further research including material characterization and hygrothermal modelling is planned for this wall to improve specifications.
- For wall assembly No. 3 with 1.5 in. rigid stone wool exterior insulation (vapour permeance of about 1200 ng/(Pa·s·m^2) (about 21 US perm)), together with an interior poly vapour barrier, the measured RH from the interior surface of its OSB sheathing consistently remains below 80% over the entire test period. Among the six wall types tested, this wall should protect the OSB with the lowest humidity level in service. The MC measured from the OSB sheathing consistently stays below 16%, even after water injection. Therefore, this wall is able to manage vapour diffusion from the interior space or incidental water leaks from the exterior.
- For wall assembly No. 4 with 1 in. XPS exterior insulation (vapour permeance of 87 ng/(Pa·s·m^2) (about 1.5 US perm)), together with an interior poly vapour barrier, the measured RH from the interior surface of its OSB sheathing remains below 80% over the entire test period. The MC measurements from the OSB sheathing slightly exceeds 16% after each phase of water injection. This wall shows limited vapour diffusion drying capacity due to the lower vapour permeance of the XPS compared to EPS or stone wool, with drying rates lower than those of wall No. 3 or No. 6 noted below.
- For wall assembly No. 5, with 1 in. thick foil faced-polyiso exterior insulation (vapour permeance close to 0), together with an interior vapour-retarding paint on its drywall, the RH measurements from the interior surface of its OSB sheathing consistently stays above 80%, suggesting high mould growth potential over the two winter seasons. This is also confirmed with the relatively high MI when the sheathing is assigned with the "Very Sensitive" mould growth classification. However, no mould is found on the interior or the exterior surface of the sheathing if the sheathing is subject only to vapour diffusion. But mould is found around and below the wetting pads. Compared to the other walls tested, this wall has lower tolerance,

when water penetrates between the impermeable exterior insulation and the wood frame, due to its minimal capacity to dry towards the exterior. Note that this assembly exceeds the current building code (e.g., National Building Code of Canada, BC Building Code) section 9.25 outboard to inboard insulation ratio requirements for the tested climate zone.

- For wall assembly No. 6 with 1.5 in. EPS exterior insulation (vapour permeance of about 130 ng/(Pa·s·m^2) (about 2 US perm)), together with an interior poly vapour barrier, the measured RH from the interior surface of its OSB sheathing consistently remains below 80% over the entire test period. The MC measured from the OSB sheathing consistently stays below 16%, even after water injection. Therefore, this wall is able to manage vapour diffusion from the interior space or incidental rain leaks from the exterior.

Table 3. Summary of hygrothermal performance of six wall assemblies in Vancouver's climate based on this test

Wall assembly	Wall features	RH level on OSB's interior surface in winter	Moisture accumulation risk on OSB due to outward vapour diffusion from humid indoor space	Drying capacity after incidental water leaks behind sheathing membrane	Overall long-term durability performance indication
No. 1 	Deep wall studs with interior poly	Below 80%	Low risk	Reasonably good drying (Drying can occur towards the exterior.)	Acceptable when it is built to be airtight
No. 2 	Double wall studs with ocSPF, together with an interior vapour-retarding paint (on foam/ drywall)	Exceeding 90% with the initial vapour-retarding paint on the foam; above 80% with another interior vapour-retarding paint on drywall	Considerable moisture accumulation risk due to high indoor RH in wintertime	Reasonably good drying (Drying can occur towards both interior and exterior.)	There is mould growth potential based on this test. The wall is not suitable for buildings with a high indoor moisture load, unless a less permeable interior vapour control is applied.
No. 3 	Highly permeable exterior insulation (1.5 in. stone wool, with a vapour permeance of 1200 ng/(Pa·s·m^2) (about 21 US perm)), together with interior poly	Below 80%	Low risk	Good drying (Drying can occur quickly towards the exterior.)	Good
No. 6 	Permeable exterior insulation (1.5 in. EPS, with a vapour permeance of about 130 ng/(Pa·s·m^2) (about 2 US perm)), together with interior poly	Below 80%	Low risk	Good drying (Drying can occur fast enough towards the exterior.)	Good

Wall assembly	Wall features	RH level on OSB's interior surface in winter	Moisture accumulation risk on OSB due to outward vapour diffusion from humid indoor space	Drying capacity after incidental water leaks behind sheathing membrane	Overall long-term durability performance indication
No. 4 	Lower permeance exterior insulation (1 in. XPS, with a vapour permeance of 87 ng/(Pa·s·m^2) ((about 1.5 US perm)), together with interior poly	Below 80%	Low risk	Acceptable drying performance (Slow drying can occur towards the exterior through the exterior insulation.)	Acceptable
No. 5 	Impermeable exterior insulation (1 in. foil-faced polyiso, with vapour permeance close to none), together with an interior vapour-retarding paint	Persistently above 80%	Considerable moisture accumulation risk due to high RH in wintertime	Poor drying (Very limited drying can occur only towards the interior when conditions permit.)	There is durability risk from outward vapour diffusion when there is a high indoor moisture load or incidental water leaks.

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1 OBJECTIVES

To assist the City of Vancouver and Province of British Columbia and later the rest of Canada in applying the new energy code requirements to wood construction, this project contributes performance data on thermally efficient walls to help identify best practices that will ensure both durable and energy efficient wood-frame construction. By testing R22 walls installed in a test hut, this project focuses on meeting the following objectives:

- To generate hygrothermal performance data on configurations of wood-frame exterior wall assemblies anticipated to be commonly used in high energy efficient buildings across Canada
- To validate hygrothermal models to be used to improve design tools for wood-frame construction
- To develop specific recommendations on durable and energy efficient wood-frame exterior wall assemblies that practitioners can readily use
- To compare findings against current building code requirements for highly insulated walls and identify any potential building code related challenges with specification or design.

2 INTRODUCTION

Building energy regulations have changed and are being implemented at an accelerated pace across Canada to meet the mandates of governments to reduce energy consumption and greenhouse gas emissions. In the Province of British Columbia, the BC Energy Step Code was enacted in April 2017 to transform the new construction of both Part 9 and Part 3 buildings with the aim of achieving "Net-Zero Energy Ready buildings" by 2032 (Government of British Columbia 2017). Given the adoption of the overall "envelope first" approach, the building envelope must be built to be highly airtight and thermally efficient to meet the new energy code requirements. The City of Vancouver requires RSI 3.85 (R22 effective) for above-grade and foundation walls of residential buildings up to six storeys (City of Vancouver 2018). This requires additional insulation, often exterior insulation over a traditional 2 by 4 or 2 by 6 wood-frame wall, or a deeper stud or double-stud wall. Following the release of the BC Energy Step Code, BC Housing updated in collaboration with its partners its illustrated guide "R22+ Effective Walls in Residential Construction in British Columbia" (BC Housing 2017). While measures to increasing the overall thermal resistance of exterior walls and the general impact of adding insulation (e.g., cavity insulation, exterior insulation) on the hygrothermal[1] performance of conventional wood frame walls are well understood, moisture-related performance data about R22 walls in the Vancouver climate are needed to:

- identify potential negative consequences of added thermal insulation and various vapour control measures,
- confirm acceptance of designs under current building code requirements,
- validate design tools, and
- improve specifications.

FPInnovations therefore initiated in 2018 a new test of six types of light wood-frame walls that meet the R22 requirement using a test hut located at its Vancouver site. This report provides analysis of the performance of

[1] The physical performance of the building envelope or other building assemblies related to the movement of heat, air, water and vapour.

these walls based on the data collected over a 19-month period. The test results will be used to improve recommendations for durable and energy efficient wood-frame wall assemblies and to validate hygrothermal modelling in next phases of this study.

The testing method used enables the comparison of the hygrothermal performance of different wall assemblies through exposing them to the same exterior and interior environment and is a popular research approach (Straube et al. 2002). Similar testing facilities are available in Metro Vancouver (Gauvin 2014; Tariku et al. 2015). This study is the first to completely focus on the impacts of a range of thermal insulation strategies/methods coupled with interior vapour control on the hygrothermal performance of R22 wood-frame walls. It has become more relevant and urgent given the fact that designers and builders nowadays face many options of thermal insulation and vapour control combinations that theoretically will meet the higher energy efficiency requirements. With highly insulated assemblies, what becomes more difficult to predict is how prone each of the combinations are to moisture-related problems (e.g., mould growth), both during construction (e.g., from trapped moisture) and post occupancy (e.g., from indoor/outdoor humidity and water leakage). This is because these higher thermally efficient solutions are likely to have reduced drying capacity and increased wetting potential, compared to conventional wood-frame construction. Conventional construction without a rainscreen cavity is known to have a major moisture hazard caused by wind-driven rain in the Vancouver climate (CMHC 1996).

When studying building envelope systems, it is important to understand the functions of each of the components under ideal conditions, and then to anticipate the system responses when conditions are not perfect or ideal. For example, the exterior sheathing, typically as the coldest moisture-sensitive structural member in the building envelope in a heating-dominated climate, is particularly susceptible to interstitial moisture accumulation and vapour condensation, when air exfiltration and/or outbound vapour diffusion occurs; or when there is any water leakage caused by defects in the building envelopes' defense lines against rain penetration. While exterior insulation is known to keep the exterior structural sheathing warmer and may thereby reduce the vapour condensation potential, exterior insulation and membrane products with different vapour permeance attributes will affect the drying if unintended wetting occurs (Armstrong et al. 2009; Smegal et al. 2012; 2013; Fox 2014; Trainor 2014; Glass et al. 2015; Glass et al. 2016; Boardman et al. 2019). Also, the interior vapour control may become more important for an energy efficient building in a heating climate since an airtight building envelope may increase the indoor humidity level even with code minimum mechanical ventilation.

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Dorian Tung	Manager, Building Systems

4 MATERIALS AND METHODS

4.1 Study Overview

This project aims to assess, under controlled interior environmental conditions, the moisture performance of six types of thermally efficient wood-frame exterior wall assemblies when exposed to the Vancouver climate. These walls, installed in a test hut built specifically for testing the hygrothermal performance of exterior wall assemblies, used different insulation strategies/materials to just meet an effective R-value of R22 (RSI3.85).

The test hut is positioned away from surrounding buildings so that it is well exposed to the elements (Figure 1) and is oriented so that each of the four walls face one of the cardinal directions. With a column spacing at 1200 mm (4 ft.), the frame of its walls is built to allow installing 10 wall panels, each measuring 1200 mm (4 ft.) wide and 2400 mm (8 ft.) tall in the north and the south orientations. It also has a double-size bay (2400 mm (8 ft.) by 2400 mm (8 ft.)) in its east-facing wall to accommodate two wall panels. A total of 12 test wall panels were built in the laboratory and installed on the test hut from June to August 2018. One replicate of the wall assemblies, labelled from No. 1 to No. 5, is installed north-facing (i.e., N1, N2, N3, N4, and N5), while a second replicate is installed south-facing (i.e., S1, S2, S3, S4, and S5). Wall assemblies No. 3 and No. 6 are installed to face east (E1, E2), with wall assembly No. 3 serving as a reference wall for these three orientations (i.e., N3, S3, E1, Figure 2).

This study focuses on measuring the moisture content (MC) of wood, the ambient environmental conditions including temperature and relative humidity (RH), and the corresponding vapour pressure gradients through each wall panel using sensors. Moisture loads, in the form of vapour (i.e., from the relatively high indoor humidity (around 50% RH) maintained by a humidifier) and liquid water (simulated by injecting water through a tube into a wetting pad pre-built into the wall) are used to stress the walls for investigating their moisture-related behaviour. Wall performance discussions in this report focus primarily on the oriented strand board (OSB) sheathing, as it is the most sensitive component to moisture accumulation.

Figure 1. Exterior of the finished test hut

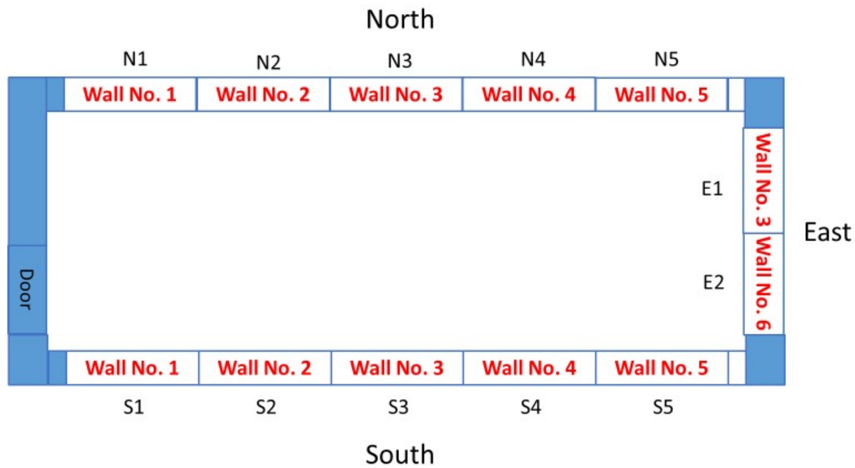


Figure 2. Layout of 12 test wall panels, in six wall assemblies and three orientations at the test hut

4.2 Test Matrix

This controlled test focuses on assessing the effects of varying insulation strategies/materials and interior vapour control measures to better investigate the effectiveness/impacts of design decisions on the test walls' hygrothermal responses. Among the six walls investigated, the thermal insulation type(s) and location(s) are the major variables. All insulation including the interior insulation installed inside the stud cavities and the exterior insulation installed outside of the sheathing membrane are commonly used materials in construction. The detailed wall assemblies are summarized in Table 1. No. 1 was similar to a traditional wall, framed with 38 mm by 184 mm (nominal 2 in. by 8 in.) dimension lumber, with the stud cavities filled with nominal R28 glass fibre batt insulation (highly vapour permeable). No. 2 was built with double wall studs (38 mm by 89 mm (nominal 2 in. by 4 in.) dimension lumber), placed at the same spacing along the interior and exterior wall faces but with a 6 mm (1/4 in.) gap between the two studs (also see Appendix XI: Figure 119). The wall cavities were filled with a highly vapour-permeable, 0.5-pcf (8 kg/m^3) open-cell spray polyurethane foam (ocSPF) (with a vapour permeance of about 1200 ng/(Pa·s·m^2) (about 21 US perm)), installed by a certified provider. Such a wall has been recently developed with a vapour-retarding paint directly sprayed on the foam's interior surface. It has become popular for building energy efficient homes with the foam providing good airtightness. The other four types of walls are split-insulated assemblies, each framed with 38 mm by 140 mm (nominal 2 in. by 6 in.) dimension lumber and having the same interior insulation (R19 compressed from nominal R20 glass fibre batt insulation) in the stud cavities. Exterior insulation has become increasingly common in wood construction. The exterior insulations applied to the four walls were rigid stone wool (38 mm (1.5 in.) thick, with a vapour permeance of about 1200 ng/(Pa·s·m^2) (about 21 US perm) in wall No. 3), extruded polystyrene (XPS, 25 mm (1 in.) thick, with a vapour permeance of about 87 ng/(Pa·s·m^2) (about 1.5 US perm) in No. 4), foil faced-polyisocyanurate (polyiso, 25 mm (1 in.) thick, with vapour permeance close to zero in wall No. 5), and expanded polystyrene (EPS, 38 mm (1.5 in.) thick, with a vapour permeance of about 130 ng/(Pa·s·m^2) (about 2 US perm) in No. 6). The vapour permeance of these exterior insulation boards decreases from the stone wool, EPS, XPS, to the foil faced-polyiso insulation. All these four split-insulated walls meet the building code (i.e., National Building Code of Canada, BC Building Code) 9.25 outboard to inboard thermal insulation ratio (0.2) for the climate of Vancouver. The ratios are specified by the codes for the purpose of keeping the exterior sheathing warm enough to prevent vapour condensation.

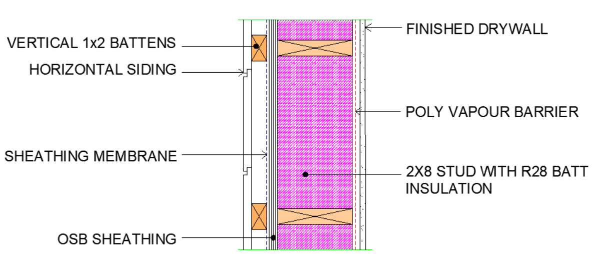
Table 1. Summary of six types of wall assemblies

<table>
<tr><th>Wall No.</th><th>Interior finish</th><th>Vapour control</th><th>Framing</th><th>Stud cavity insulation</th><th>Sheathing</th><th>Sheathing membrane</th><th>Exterior insulation</th><th>Cladding</th><th>Effective R</th></tr>
<tr><td>1</td><td>Regular latex paint on drywall</td><td>6 mil poly vapour barrier</td><td>2x8 @ 16 o.c.</td><td>R28 fiberglass batt</td><td rowspan="6">OSB sheathing, 7/16” thick</td><td rowspan="6">Spun-bonded polyolefin membrane</td><td>-</td><td rowspan="6">Painted hardboard siding installed on 1x2 battens to create a rainscreen cavity</td><td>22.4</td></tr>
<tr><td>2</td><td>Regular latex paint on drywall</td><td>Vapour-retarding paint on foam, on drywall*</td><td>2x4 @ 16 o.c. double stud with ¼” gap (using 2 by 8 for perimeter)</td><td>ocSPF</td><td>-</td><td>22.4</td></tr>
<tr><td>3</td><td rowspan="2">Regular latex paint on drywall</td><td rowspan="2">6 mil poly vapour barrier</td><td rowspan="4">2x6 @ 16 o.c.</td><td rowspan="4">R20 fiberglass batt</td><td>1½” rigid stone wool (R6)</td><td>23.0</td></tr>
<tr><td>4</td><td>1” XPS (R5)</td><td>22.0</td></tr>
<tr><td>5</td><td>Vapour retarder paint on drywall</td><td>Vapour-retarding paint</td><td>1” foil faced-polyiso (R6.2)</td><td>23.2</td></tr>
<tr><td>6</td><td>Regular latex paint on drywall</td><td>6 mil poly vapour barrier</td><td>1½” type 2 EPS (R6)</td><td>23.0</td></tr>
</table>

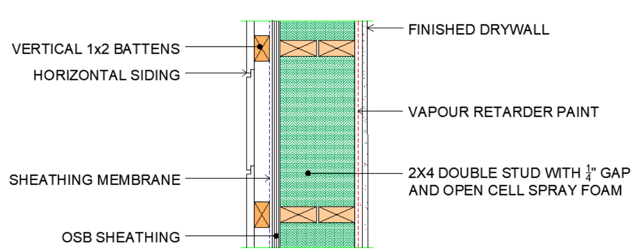
Note: 2×4/2×6/2×8: 38 mm by 89mm/38 mm by 140 mm/38 mm by 184 mm dimension lumber; poly: polyethylene membrane sheet; XPS: extruded polystyrene exterior insulation; EPS: expanded polystyrene exterior insulation; polyiso: foil faced-polyisocyanurate board; all drywall in thickness of ½ in. (12.7 mm). R20 batt insulation: nominal R20 compressed in nominal 6 in. deep-stud cavity to have an effective R-value of R19. “o.c.” means “on centre”.

*There was a vapour-retarding paint initially applied on the foam and another vapour-retarding paint was applied on the drywall of wall panels N2 and S2 on November 26, 2019 to increase the wall’s resistance to outward vapour diffusion.

Wall No. 1



Wall No. 2



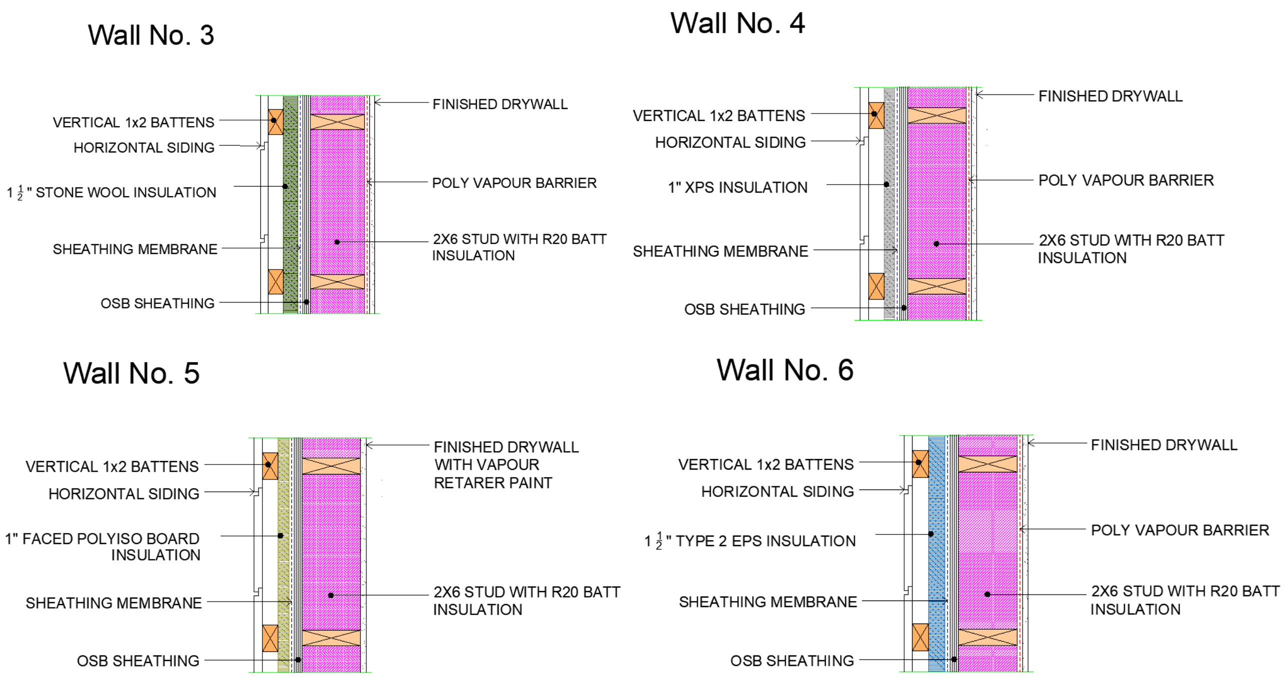


Figure 3. Schematics to show the test wall assemblies

Another major variable is the interior vapour control method, which was selected based on the insulation used; its installation follows common practices in the building industry. Wall No. 2 initially had a vapour-retarding paint applied directly on the interior surface of the ocSPF by the foam installer. After assessing its preliminary wall performance, the foam installer applied on the drywall of wall panels N2 and S2 on November 26, 2019 another vapour-retarding paint, presumed to have lower vapour permeance than the initial paint, to increase the wall's resistance to outward vapour diffusion and to observe changes in the wall's behaviour. Wall No. 5 had a vapour-retarding paint applied on the drywall at the time of construction because the foil faced-polyiso exterior insulation has, based on a dry cup test (ASTM 2010, see Appendix I), vapour permeance close to zero, qualifying it as a vapour barrier (below 60 ng/(Pa·s·m^2)) based on the National Building Code of Canada (NRC 2015). The use of a vapour-retarding paint aims to maintain some level of drying capacity towards the interior and avoids sandwiching the wood frame between two vapour barriers. The other four walls, No. 1, No. 3, No. 4, and No. 6 all have 6 mil polyethylene (poly) sheeting, a traditional vapour barrier, installed on the outside of the drywall. Except for wall No. 5, regular finishing consisting of one coat of primer and two coats of latex top finish was applied on the drywall by a drywall contractor. Acoustic caulking was generously applied on the perimeter frame of each wall before the sheet poly or the drywall was installed to further improve the airtightness of each wall. Small samples of the major materials including OSB sheathing, drywall (with or without paint), and exterior insulation materials were cut from the same batch of materials used to build the test walls and tested for vapour permeance for use in validation of hygrothermal modelling in the future. The test with a small replicate (3-6) indicated that the drywall painted with regular paint had a vapour permeance of about 500 ng/(Pa·s·m^2) (about 9 US perm) and that with the lower permeance paint applied on wall assembly No. 5 had a vapour permeance close to 300 ng/(Pa·s·m^2) (about 5 US perm). More testing is planned.

Orientation is also a major variable. It is an important factor affecting building envelope hygrothermal performance since orientation affects localized climatic conditions, such as solar radiation, RH, wind, and wind-driven rain. For example, south-facing walls, being more exposed to solar radiation, usually have better drying performance than north-facing walls. Related to potential impacts (e.g., rain penetration, inward vapour drive) caused by rain, the prevailing direction of wind-driven rain in Metro Vancouver is from the east, with winter being the predominant rainy season. No rain leakage was anticipated in this study, as all wall panels were built and installed carefully to specifications, and under dry (ideal) conditions. Although, wind-driven rain may affect the micro-climate inside the rainscreen cavity, particularly when water is absorbed by and transmitted through the cladding, the heavy painted hardboard siding used is not a highly absorptive material.

4.3 Preparation of Test Walls

Spruce-Pine-Fir (S-P-F) dimension lumber in three depths (89 mm (nominal 4 in.), 140 mm (6 in.), and 184 mm (8 in.), and OSB exterior sheathing (7/16 in. (11 mm) thick) were used to frame these walls. White spruce was identified to be the predominant species in the lumber package. With a standard spacing of 16 in. (400 mm) on centre between studs, each wall panel had three stud cavities. To simulate rain leaks during the test, a wetting pad was installed on the exterior surface of the sheathing for injecting water based on a method originally developed by Dr. John Straube and his team at the University of Waterloo (Smegal et al. 2012; Gauvin 2014; Trainor 2014). The wetting pad, formed from a type of shop-use paper towel and measuring about 11 in. (275 mm, width) and 10 in. (260 mm, height), was stapled on the sheathing to act as a water storage medium. It was located at about ¼ of the wall height (i.e., with its top at a height of 24 in. (600 mm) from the bottom) (Appendix XI: Figure 120). A small plastic distribution tube, with an inside diameter of 1/4 in. (6 mm) was installed on top of the paper towel. It had three small holes pre-drilled along the width of the wetting pad for uniformly distributing water to the paper towel. One end of the tube was blocked, while the other was accessible from the interior of the test hut for injecting water.

One sheet of a commonly used vapour-permeable spun-bonded polyolefin sheathing membrane (with a vapor permeance of about 1700 ng/(Pa·s·m^2) (30 US perm)) was installed to cover the OSB sheathing by stapling the membrane onto the four edges of each wall frame. The edges (including the sheathing membrane that partially overlapped the plates and outer studs) were then sealed with a continuous self-adhered vapour impermeable roofing membrane to provide a separation of each test wall panel from its surrounding structure and to ensure that the sheathing membrane would remain airtight. The strapping, nominal 1 in. (actual 19 mm) in depth, was installed to create a ventilated rainscreen cavity behind a heavily painted hardboard siding. The top and bottom vents were covered with fiberglass bug screen.

From the interior side, a set of sensors was installed in the middle cavity of each wall for measurements. It included six pairs of resistance-based pin-type moisture sensors for measuring the OSB's MC at six heights, two pairs of pins for measuring a wall stud's MC at different wall cavity depths, and four RH/T sensors for measuring the environmental conditions across each wall assembly (Table 2). The moisture pins were uncoated stainless screws and inserted into the wood to a depth of about 1/4 in. (6 mm, i.e., at mid-thickness of the OSB sheathing), anticipated to detect the highest MC between the two pins for the inner half of the sheathing. Each pair of moisture sensor has a combined temperature probe to note the local temperature for correcting the MC readings. Considerable effort was directed at measuring the OSB's MC and service environment given the important implications they provide for durability. The six moisture sensors for each sheathing were expected to cover moisture content differences attributed to: 1) material properties (e.g., related to wood species and density, resin content), 2) micro-climate (e.g., the variations caused by air movement (e.g., buoyancy), if any, along the sheathing plane), and 3) injected water from the wetting pad (sensors O3, O4, and O5 were installed interior to the wetting pad). A small calibration study was conducted to compare the resistance-based MC measurements to oven dry-based gravimetric MC under four humidity conditions for the batch of OSB used. Due to the large variation between and within OSB panels, it was later decided to use a calibration equation specifically generated for OSB by the US Forest Products Laboratory based on very large sample sizes that took into account the effects of both temperature and humidity (Boardman et al. 2017).

Table 2. List of sensors installed in each test wall panel

Sensor type	Purpose	Location of sensor	Label of reading	Note
Combined MC and temperature	Measuring OSB's MC, corrected with temperature. All sensors are inserted from the interior surface along the central line.	6 in. (150 mm) from the top	O1	All MC readings of OSB are based on calibration conducted by US FPL (Boardman et al. 2017)
		At mid-height (i.e., 4 ft. (1200 mm) from the bottom)	O2	
		23 in. (580 mm) from the bottom	O3	These three are located interior to the exterior wetting pad.
		19 in. (475 mm) from the bottom	O4	
		14 in. (360 mm) from the bottom	O5	
		6 in. (150 mm) from the bottom	O6	
	Measuring a stud's MC, i.e., the left stud of the middle cavity, at mid-height	Close to OSB	L1	Calibration based on white spruce (Garrahan 1989)
		Close to drywall	L2	
Combined RH and temperature	Measuring the ambient environment including temperature and RH across each wall panel	Sensor "RH/T1", on the rainscreen cavity side of the sheathing membrane or exterior insulation, at mid-height	T1, RH1	
		Sensor "RH/T2", on the interior face of the OSB sheathing, at mid-height	T2, RH2	
		Sensor "RH/T3", at about 19 in. (475 mm) from the bottom	T3, RH3	Interior to the exterior wetting pad
		Sensor "RH/T4", exterior to the poly vapour barrier when it is present, or exterior just to drywall when there is no poly.	T4, RH4	
Combined RH and temperature	Measuring the indoor environment including indoor temperature and RH	Indoor RH/T sensors installed at various locations inside the test hut	Indoor T, Indoor RH	The readings from two selected sensors are used for reporting

The four RH/T sensors, labeled from RH/T1 to RH/T4, were installed to measure changes in temperature and RH and correspondingly the vapour pressure across each wall assembly. The measurements of RH/T1, RH/T2 and RH/T4, all measured from mid-height, were used to assess the general service environment, while RH/T3 was used to indicate the impact of water injection on the interior surface of the OSB sheathing. For wall assembly No. 2, in which ocSPF was installed, no (RH/T4) sensor was installed behind its drywall to avoid damaging the continuous vapour-retarding paint sprayed on the foam. There was a total of about 160 sensors and 17 data loggers used to monitor these test wall simultaneously. The data from each sensor were collected at a 15 min interval and averaged to obtain hourly measurements. Further information about the instrumentation can be found in Appendix X and a previous report of this study (Wang 2019a).

4.4 Indoor Environment and Water Injection

Except for the summer months[2], the indoor environment of the test hut was maintained at a target condition of 21°C and 50% RH[3], through controlling the radiant heating system built into the floor and the use of a humidifier (Aircare EP Series). For measuring the indoor environmental conditions, three types of sensors, 20 in total, were installed inside the test hut to measure the variations at different locations representing the "indoor conditions" and to compare the different types of sensors. It is known that RH measurements typically have much higher levels of uncertainty than measuring temperature, and most humidity sensors have a range of accuracy from ±3% to ±5% RH (Appendix X). A high-precision handheld calibration meter (Vaisala HUMICAP® HM70) was used to compare its measurements to those from the indoor RH/T sensors. Two sensors (the same type installed inside the test walls), being located close to wall panels N2 and S2, respectively, were found to show very small differences between their readings[4] and had the closest measurements to those from the calibration meter. Their average measurements[5] are therefore used to represent the indoor environment of the test hut.

To simulate water leaks from, for example wind driven rain, and to further stress the test walls for assessing their drying performance, water was injected into the wetting pad located on the exterior surface of each OSB sheathing (see the wetting pad installed on OSB in a picture Figure 120) in three phases in different seasons. The injection was provided once or twice daily over five consecutive days in late July 2019, nine days separated by a weekend in November 2019, and 10 days separated by a weekend in January 2020. A total of around 200 mL of water was injected into each wall in each phase (see Appendix II,

Table **5** for details), simulating potential wind-driven rain penetration in this climate. However, there was difficulty in getting water into wall panel N5, particularly during phases B and C, probably due to blockage of the tube. Consequently, the amounts of water injected into this wall panel in these two phases are much lower than the target amounts.

5 RESULTS AND DISCUSSION

This report shows the hygrothermal performance of the test walls based on the data collected over a period of 19 months from mid-October 2018 to mid-May 2020; this period covers two winter seasons and one summer. The data were processed and presented in Excel charts. To facilitate the processing of these large data files, the interval of data points in a few charts below was reduced to every three hours, instead of hourly. Aside from the charts used for discussions, additional charts are provided in the appendices (Appendices III-IX) to provide further details. Overall, the measurements and data collection are smooth and can be used to examine the effects of the various study parameters. The limited data loss was the result of a temporary loss of battery power to several data loggers, and the malfunctioning of a few sensors during the test. The data loss has little impact on the test results and is largely excluded from the discussions below.

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[2] The test hut was not equipped with air conditioning.

[3] When the exterior environment has RH of 90% @ 5°C in the winter in Vancouver, the RH will drop below 40% when it is heated to 20°C based on a psychrometric chart, without taking into account the moisture generated indoors, such as cooking and showering etc.

[4] Their differences in temperature readings are mostly below 0.1 °C and those in RH measurements were mostly below 1%.

[5] There were data losses from one of these two sensors for a few short periods of time during the test; the measurements from one functioning sensor when the other had problem with data recording were then used to show the indoor environment.

5.1 Environmental Boundary Conditions

The interior and exterior boundary conditions are the most important factors influencing the hygrothermal behaviour of the test walls. An overarching principle of design building envelope assemblies is managing the environmental loads (e.g., thermal, moisture) imposed by both the interior and the exterior environments. In terms of moisture-related performance, an exterior wall is required to minimize wetting; but if wetted, to facilitate drying at the exterior and/or the interior boundaries.

5.1.1 Indoor Environment

The target indoor condition of 21°C and 50% RH, corresponding to an indoor vapour pressure of about 1200 Pa, is a typical but relatively high indoor moisture load for the building envelope found in multi-unit residential buildings across Metro Vancouver during the winter. A recent monitoring study conducted by FPInnovations on seven suites in a six-storey, energy efficient wood-frame building in Vancouver found the indoor RH mostly remained in the 25-45% range in the winter and about 35-55% in the summer, and the indoor temperature was mostly in the 20-28°C range[6] (Wang 2019b). Relatively high indoor humidity of 40-50% RH in winter in this climate is also reported based on monitoring by other researchers (e.g., Finch 2007). This target indoor condition is consistent with design recommendations for the Vancouver climate based on building codes (e.g., NRC 2015) and the ASHRAE 160 standard (ASHRAE 2016).

Overall, the environment inside the test hut was maintained as expected. The temperature (i.e., indoor T in Figure 4) was well maintained around 21°C, except in the summer when the temperature at times rose to 26°C. The indoor RH shows larger deviations. It started higher in the beginning of the test; but was well below 50% when the humidifier lost power on a few occasions. The RH had a large spike, reaching 80% in late May to early June 2019 before the humidifier was turned off for the summer.

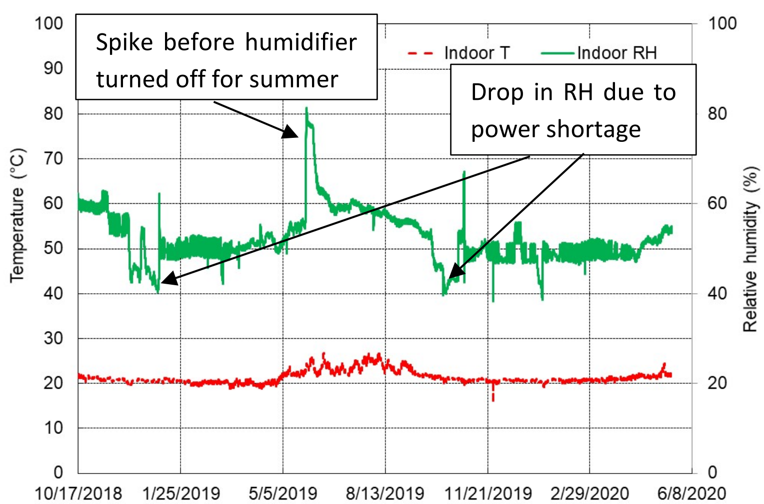


Figure 4. Measured hourly indoor relative humidity (RH) and temperature (T) from the test hut over the entire test period

[6] These indoor temperature and RH also generate an indoor vapour pressure around 1200 Pa in wintertime.

5.1.2 Environmental Conditions in Rainscreen Cavities

The ventilated rainscreen cavity, instead of the exterior environment that the hut is exposed to, is defined in this report as a simplified but more relevant exterior boundary for comparing wall performance. The measured temperature (T1) and RH (RH1) from each wall's rainscreen cavity provides the condition that influences how vapour diffuses across each test wall panel (see section 5.4). Data from the weather station[7] located on the east end of the roof ridge may not reflect the variations in the exposure conditions that each wall will experience (e.g., north- and south-facing).

As expected, orientation is the largest factor for the environmental conditions in the rainscreen cavities, primarily due to solar effects. Among the measurements from the sensors (RH/T1) installed in the rainscreen cavities of 12 wall panels, the temperature and RH measurements from each orientation (north, south[8], or east) are similar and, as expected, fluctuates with the exterior environment (see Appendix IX for detailed figures). The north-facing rainscreen cavities in general have lower temperature than the south-facing rainscreen cavities (Figure 5). Correspondingly, the north shows higher and the south shows lower RH (Figure 6). In general, the two east-facing walls' rainscreen cavities have temperature and RH between those of the north- and the south-facing wall panels. The measured temperature and RH from the rainscreen cavities well reflect the coastal climate of Vancouver, with the winter being mild and damp and the summer being warm and drier, as previously reported (e.g., Finch 2007). Most discussions below about moisture-related performances, such as the service environment and the drying capacity of the OSB sheathing, will focus on observations during the winter due to the associated higher moisture risk, compared to the summer in this climate.

[7] A weather station was installed on the roof of the test hut; however, data collection was not continuous throughout the test due to issues caused by lack of maintenance and calibration. The weather data used in the parallel hygrothermal modelling was decided to use the climatic data provided by Environment Canada based on measurements at the Vancouver International Airport. The test hut is very close to the Vancouver International Airport, which justifies use of the data from an official source.

[8] The RH probe in wall panel N3 started malfunctioning after about four months in service by showing readings well above 100%; the data from it were therefore discarded. The average RH measurements from its two adjacent rainscreen cavities (i.e., wall N2 and N4) are used to represent the RH1 of wall N3 for related analysis.

- North T1 (north facing) – an average of five wall panels N1, N2, N3, N4, and N5
- South T1 (south facing) – an average of five wall panels S1, S2, S3, S4, and S5
- East T1 (east facing) – an average of two wall panels E1 and E2

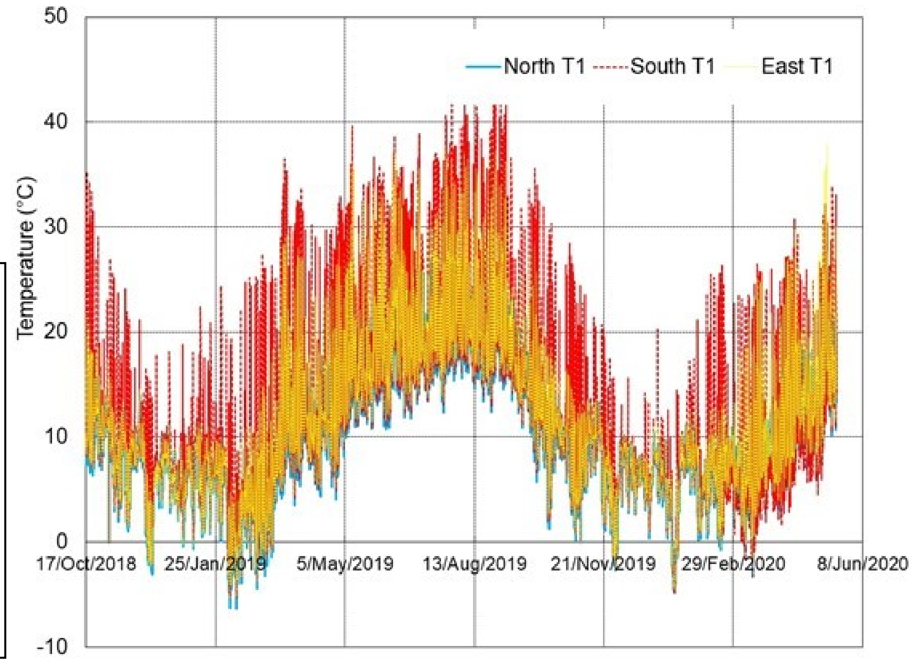


Figure 5. Average hourly temperature in the rainscreen cavities in each orientation over the entire test period

- North RH1 (north facing) – an average of four wall panels N1, N2, N4, and N5
- South RH1 (south facing) – an average of five wall panels S1, S2, S3, S4, and S5
- East RH1 (east facing) – an average of two wall panels E1 and E2

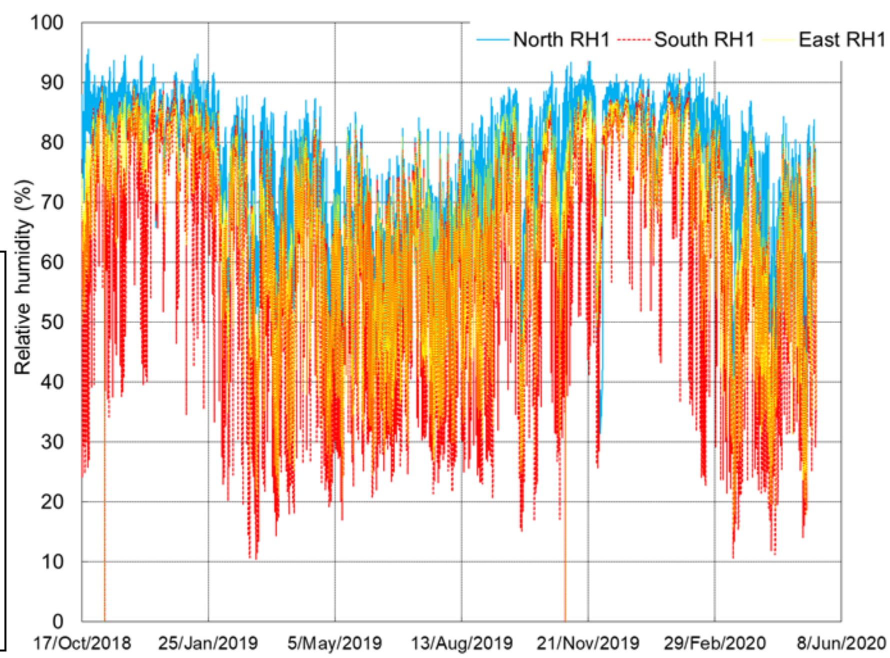


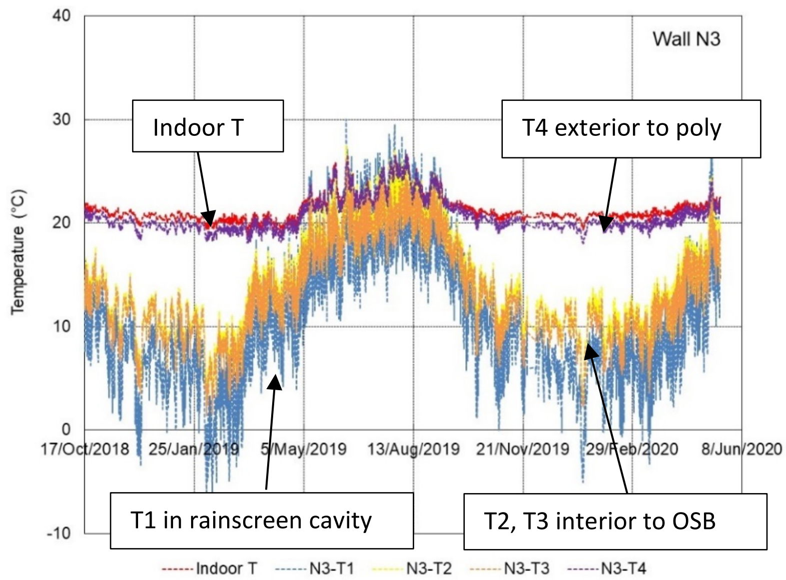
Figure 6. Average hourly relative humidity in the rainscreen cavities in each orientation over the entire test period

5.2 Interstitial Environment

The interstitial environment, i.e., the conditions such as temperature and RH inside a wall defines the moisture service environment of wood components (e.g., structural sheathing, wall studs etc.) and thereby provides implications about their long-term durability performance. Fungi, for example, will thrive on wood under warm and damp conditions. Under warm conditions (e.g., 20-30°C), an RH of 80% is commonly taken as the threshold for initiation of mould growth on wood-based products (Viitanen and Paajanen 1988; Nielsen 2004). This study focuses on assessing the impact of wall assembly design on durability performance of the OSB exterior sheathing due to its higher susceptibility to moisture issues, compared with other wood components (e.g., wall studs). According to the standard ASHRAE 160: Criteria for Moisture-Control Design Analysis in Buildings for predicting mould growth and assume that the OSB sheathing used in the test walls falls into the “Very Sensitive” class, i.e., the worst-case scenario for untreated wood based on the standard, or into the less severe “Sensitive” class (ASHRAE 2016), 80% is expected to be the lower limit for mould growth at a temperature of 20°C. Higher RH and warmer conditions typically accelerate mould growth, and may even cause metal corrosion and wood decay, which can consequently impact connections and structural integrity. This section first provides a general picture of the temperature and RH profiles, using test wall No. 3 as an example (sections 5.2.1 and 5.2.2); it then focuses on the service environment of the OSB sheathing in the different wall types (sections 5.2.3, 5.2.4, and 5.2.5).

5.2.1 Temperature Profiles across Wall Assembly No. 3 in Three Orientations

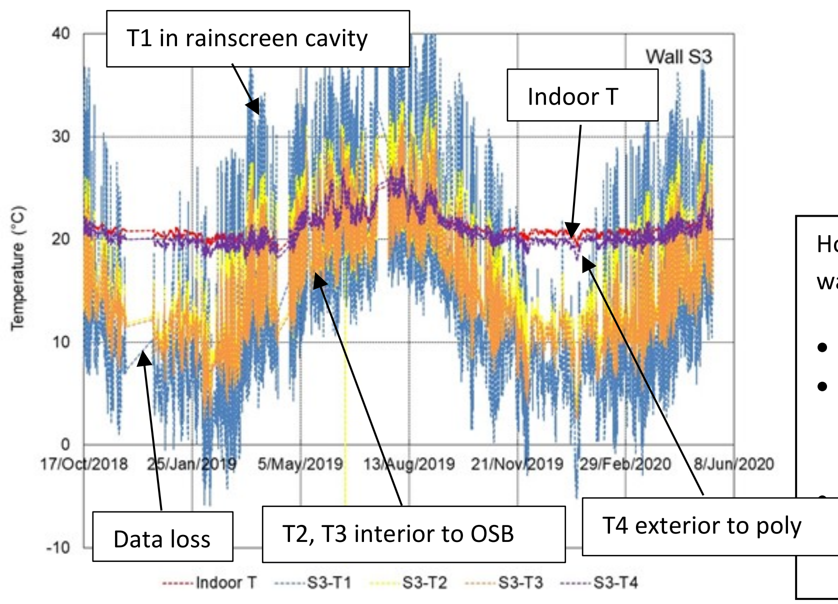
The temperature across an exterior wall in general increases from the outdoor to the indoor space in a heating-dominated climate including Vancouver’s. This trend is well illustrated in the north-facing wall panel N3, with Figure 7 clearly showing that the temperature largely increases: from the rainscreen cavity (T1), to the interior surface of the OSB sheathing (T2 at mid-height and T3 at the height of the wetting pad), to the exterior surface of the poly vapour barrier (T4), and finally at the indoor space (indoor T). Wall assembly No. 3 is taken as an example here since it has test wall panels in three orientations, i.e., N3, S3, and E1. There are also clear temperature differentials between the rainscreen cavity and the OSB sheathing, where they are separated by exterior insulation. As expected, the measurements from the exterior side of the wall, including the rainscreen cavity (T1) and the OSB sheathing (T2, T3) tend to have greater fluctuations resulting from larger influence of the uncontrolled exterior environment, compared to the indoor temperature. Among the three orientations, the temperature measurements show the largest fluctuations in the south-facing wall S3 (Figure 8), followed by the east wall (E1, Figure 9); the north wall (N3) has the smallest fluctuations. Wall panel S3 also has the highest frequency of instances when the exterior side temperature measurements exceeding the indoor temperature, indicating inward heat flow. This occurs even in relatively cold months. Very small temperature differences (i.e., vertical stratifications) are observed between the two measurements (T2, T3) at different heights of the same OSB sheathing plane (on its interior surface), suggesting relatively uniform heat flow along the wall height. This is therefore not discussed.



Hourly temperature profile (North-facing wall panel N3):

- In the rainscreen cavity (T1)
- On the interior surface of the OSB sheathing (T2 at mid-height, T3 at the height of the wetting pad)
- On the exterior surface of the poly vapour barrier (T4)
- In the indoor space

Figure 7. Hourly temperature profile in wall panel N3 from the rainscreen cavity to the indoor space



Hourly temperature profile (South-facing wall panel S3):

- In the rainscreen cavity (T1)
- On the interior surface of the OSB sheathing (T2 at mid-height, T3 at the height of the wetting pad)
- On the exterior surface of the poly vapour barrier (T4)

Figure 8. Hourly temperature profile in wall panel S3 from the rainscreen cavity to the indoor space

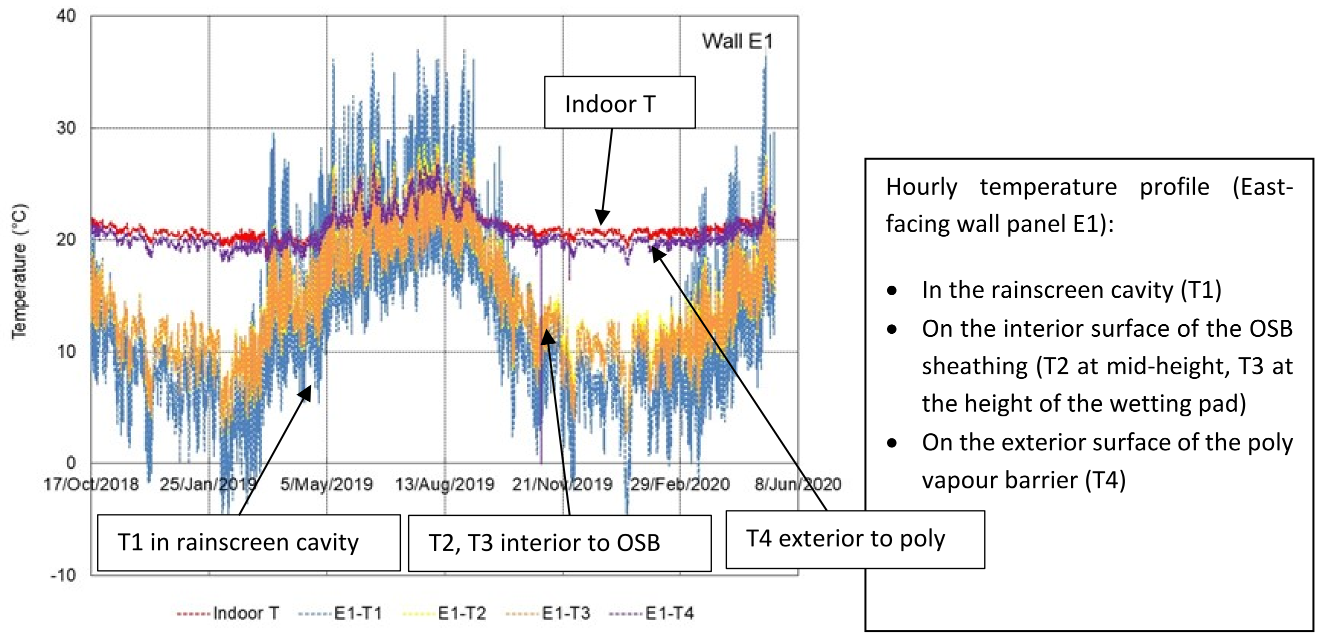


Figure 9. Hourly temperature profile in wall panel E1 from the rainscreen cavity to the indoor space

As expected, the OSB sheathing remains the warmest in the south-facing wall panel S3 and the coldest in the north-facing wall panel N3 (Figure 10). The north-facing wall panels, being the most likely to suffer from poor drying due to the smallest solar effects, are the focus for examining the moisture-related performances below.

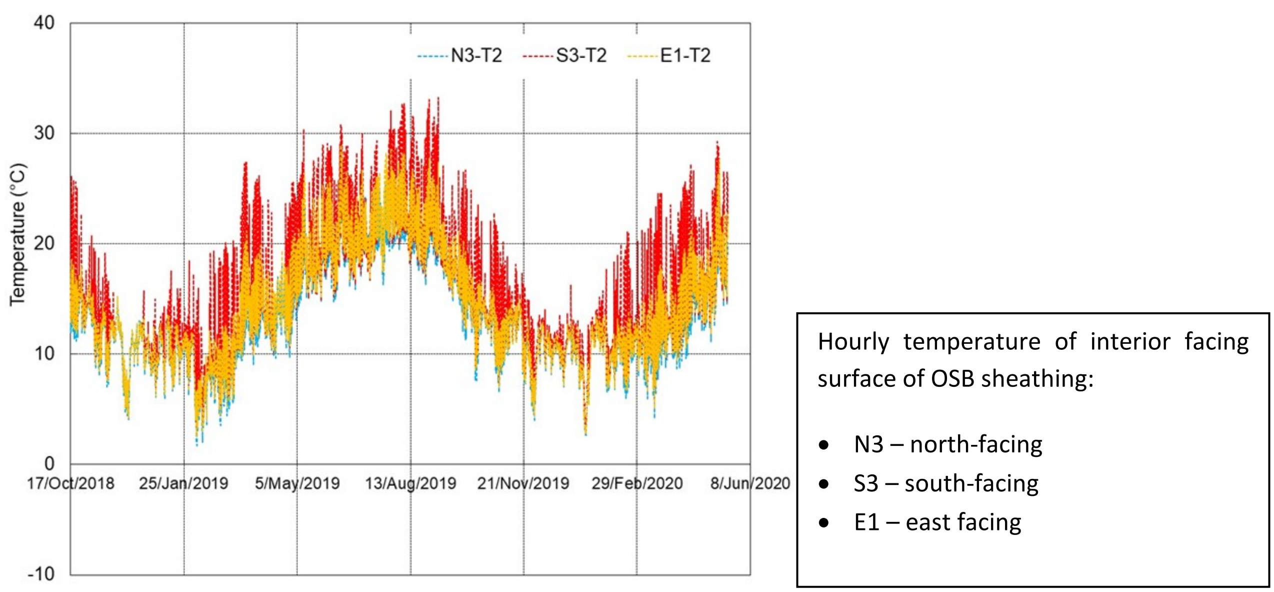


Figure 10. Comparison of interior surface temperature of OSB in three orientations of wall No. 3

5.2.2 Relative Humidity Profiles across Wall Assembly No. 3 in Three Orientations

The RH in a given space is inversely related to the temperature, when there is no moisture exchange with the outside. Taking the same test wall panels N3, S3, and E1 as examples, in general the rainscreen cavities (RH1), being closest to the exterior environment, have the highest and also the largest fluctuations in humidity levels, compared to the RH measurements taken from the interior locations (Figure 11; Figure 12; Figure 13). The RH1 measurements from test wall panel N3 are around 90% in the winter and reduces to around 60% in the summer. By comparison, the RH1 measurements are the lowest (i.e., the driest) in the south-facing wall panel S3, followed by wall panel E1, and remain the highest in wall panel N3.

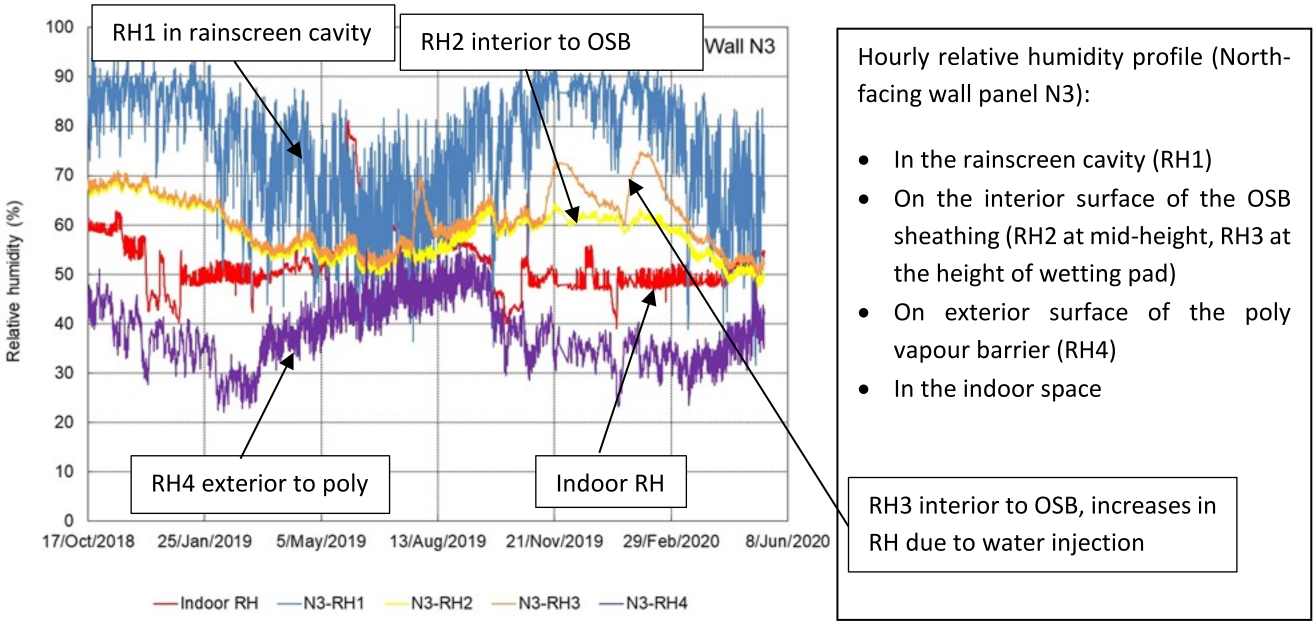


Figure 11. Hourly relative humidity profile through the wall thickness for wall panel N3

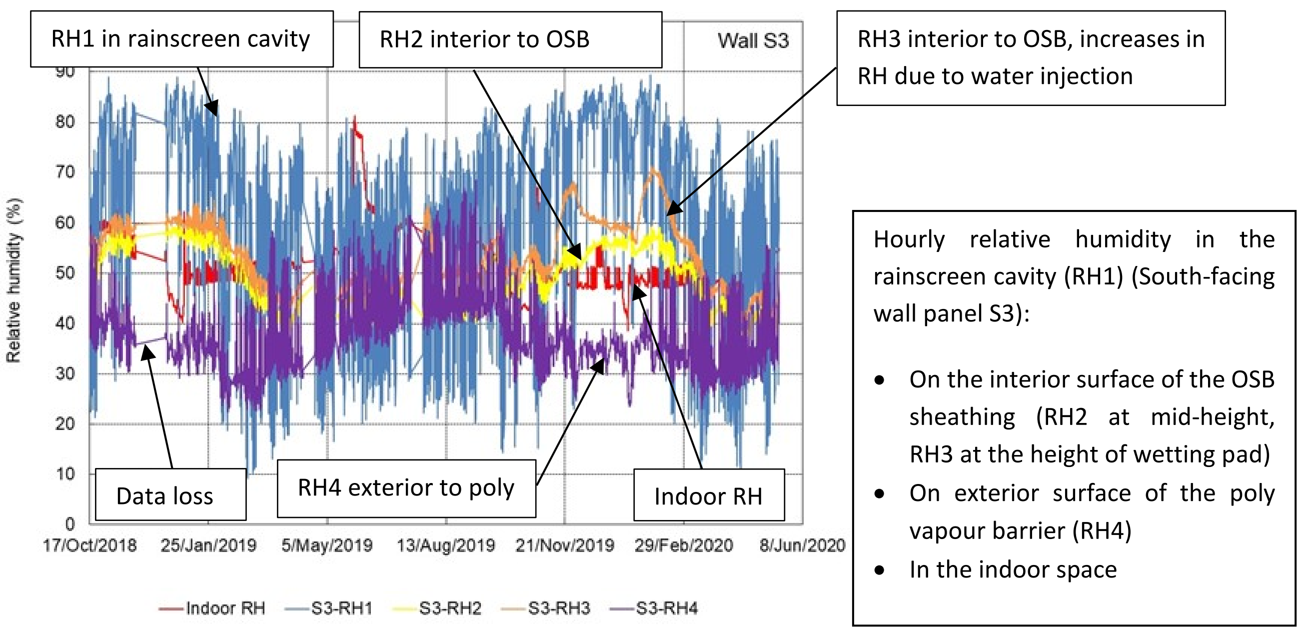


Figure 12. Hourly relative humidity in the rainscreen cavity (RH1) for wall panel S3

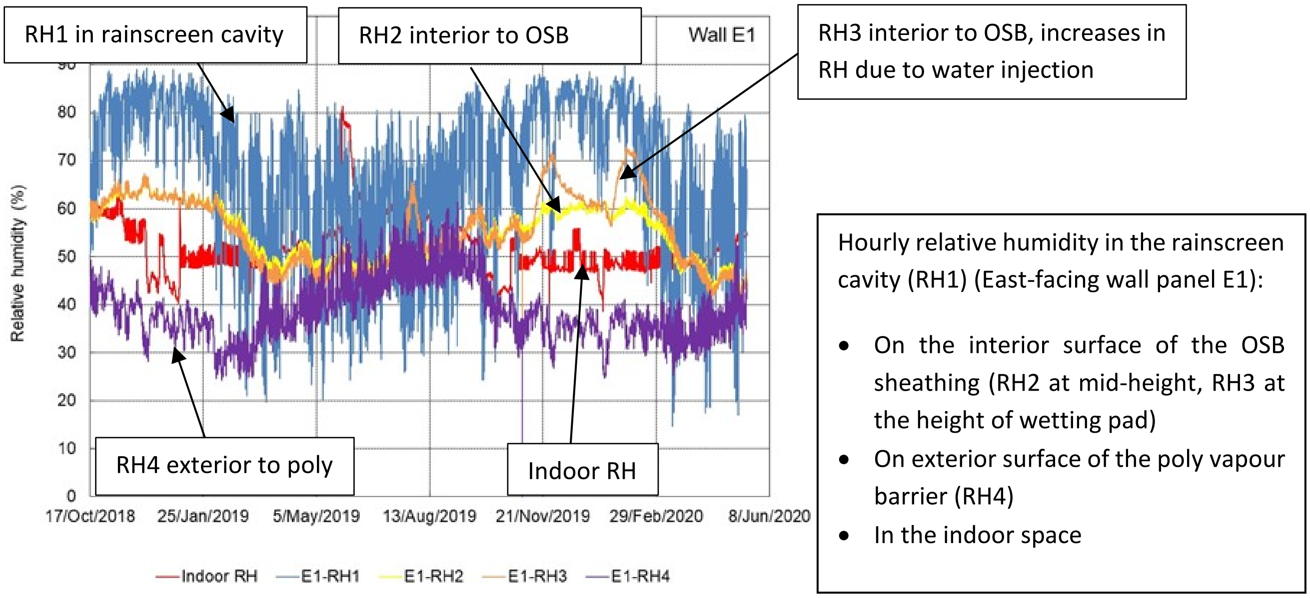


Figure 13. Hourly relative humidity in the rainscreen cavity (RH1) for wall panel E1

Regarding the ambient environment close to the OSB sheathing, Figure 14 clearly shows the south-facing wall panel S3 has the lowest humidity levels and the north-facing N3 has the highest humidity, based on the RH measurements (RH2) from the interior surface of the OSB sheathing (at mid-height). The service environment of the OSB sheathing is discussed in detail at the following sections 5.2.3, 5.2.4, and 5.2.5. Figure 14 also indicates the service environment of the sheathing is slightly drier in the second winter than in the first winter.

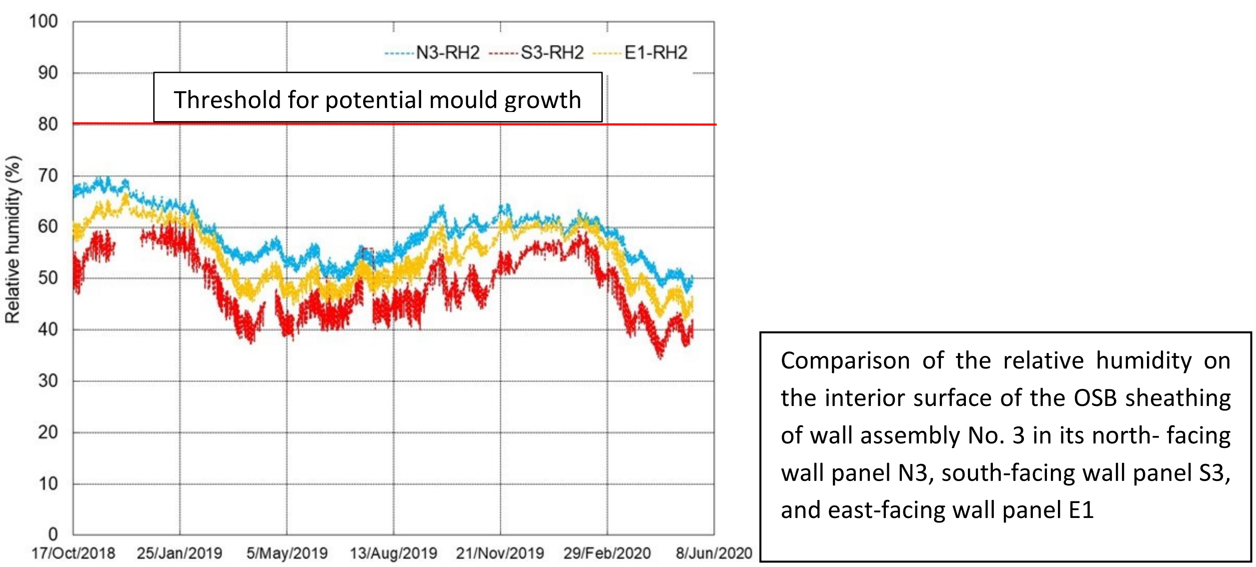


Figure 14. Relative humidity on the interior surface of the OSB sheathing of wall assembly No. 3

5.2.3 Service Environment of OSB Sheathing: Effect of Exterior Insulation

Installing exterior insulation is often considered an effective solution to improving both thermal performance and durability of building envelope assemblies. Its effects on the service environment of the OSB sheathing of the test walls are discussed in this section based on the measured temperature (T2) and RH (RH2) from the interior surface of the sheathing of each test wall panel.

5.2.3.1 Effect of Exterior Insulation on OSB Sheathing's Temperature: Comparison among Test Walls

Exterior insulation makes the structural sheathing warmer. This is demonstrated in Figure 15, comparing a split-insulated test wall (No. 3) to a deep-cavity wall without exterior insulation (No. 1), both in the north orientation. The OSB sheathing of wall panel N3 is warmer than that of wall panel N1, approximately by 2°C to 4°C over the winter from October 2018 to May 2019. Without exterior insulation, the T2 measurements from the test wall panels N1 and N2, both deep-cavity walls, are very close (Figure 16). Comparing the four split-insulated wall assemblies, i.e., walls No. 3, No. 4, and No. 5 in the north orientation (based on the test wall panels N3, N4, and N5, Figure 17) , or the two walls No. 3 and No. 6 in the east orientation (based on wall panel E1 and E2, Figure 18) suggests that other properties of the insulation (i.e., such as vapour permeance) have little impact on its capacity to keep the sheathing warmer. Among the four types of exterior insulation products, the stone wool in wall No. 3, the foil-faced polyiso in wall No. 5, and the EPS in wall No. 6 (all about R6) have slightly higher thermal insulation value than the XPS (R5) in wall No. 4 and consequently result in slightly warmer sheathing in cold weather. Elevated temperature generally accelerates vapour diffusion and moisture evaporation, and thereby improves the drying capacity.

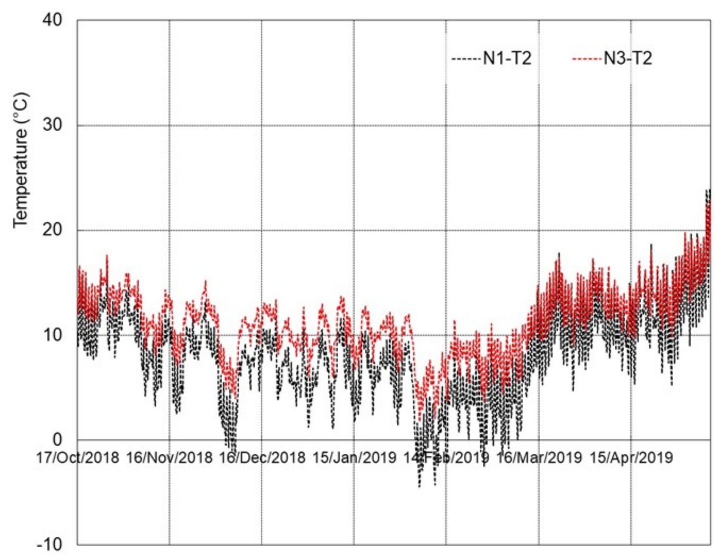


Figure 15. Temperature (T2) on the interior surface of the OSB sheathing of north-facing test wall panels N1 without exterior insulation and N3 with stone wool exterior insulation over the first winter

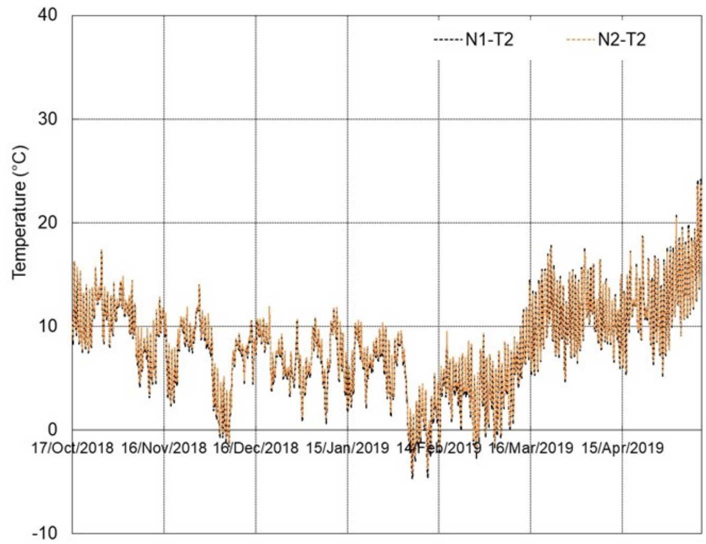


Figure 16. **Temperature (T2) on the interior surface of the OSB sheathing of north-facing test wall panels N1 and N2, neither with exterior insulation over the first winter**

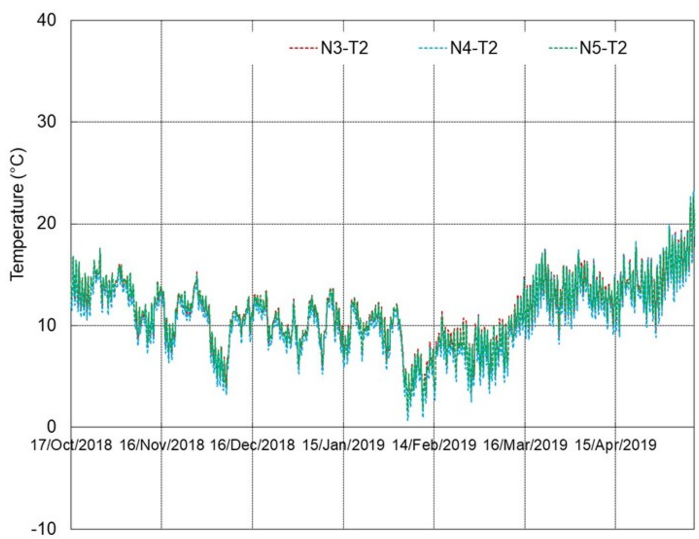


Figure 17. **Temperature (T2) on the interior surface of the OSB sheathing of north-facing test wall panels N3 (stone wool), N4 (XPS) and N5 (polyiso), all with exterior insulation over the first winter**

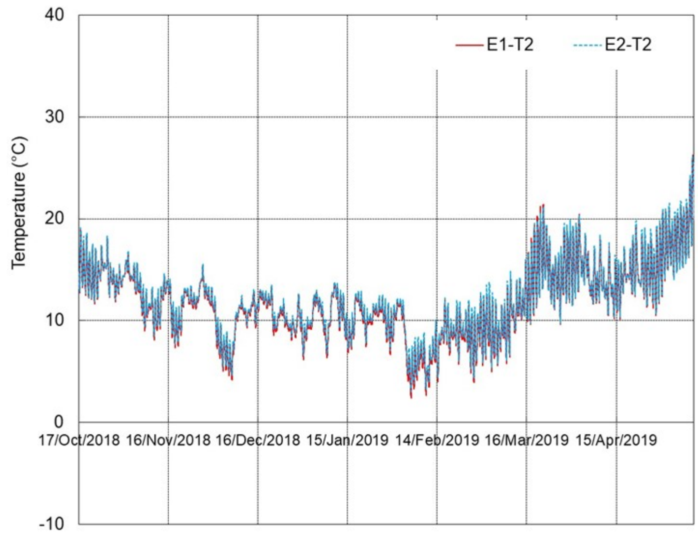


Figure 18. Temperature (T2) on the interior surface of the OSB sheathing of east-facing test wall panels E1 (stone wool) and E2 (EPS), both with exterior insulation over the first winter

5.2.3.2 Effect of Exterior Insulation on OSB Sheathing's Temperature: Comparison with Dew Point

The vapour condensation potentials on the interior surface of the OSB sheathing resulting from air exfiltration when the walls are not built to be airtight are roughly compared for these test wall panels. To assess risk of condensation on the interior surface of the OSB sheathing, the percentage is calculated between the total number of hours when the sheathing temperature falls below the dew point of the interior air and the total number of hours of the test duration, based on the measured hourly indoor temperature, RH, and the temperature from the interior surface of the OSB sheathing (i.e., T2 from each wall) over the entire year of 2019. Dew point is the temperature to which the air-borne water vapour will condense to form liquid water when it is in contact with a colder surface, i.e., the interior surface of the OSB sheathing in this case. The dew point of the interior air is calculated using the following three equations.

First for calculating vapour pressure, the saturated vapour pressure is calculated based on the measured temperature T (°C) using Equation 1. The (partial) vapour pressure is then calculated based on the measured RH (%) using Equation 2 at the same location. Saturated vapour pressure is the maximum vapour pressure exerted by vapour due to water evaporation at a given temperature in a closed system. Partial vapour pressure is the actual vapour pressure given the amount of water molecules at the given temperature in the space. Elevated temperature increases the vapour pressure when the RH remains the same in the environment.

$$\text{Saturated Vapour Pressure } Ps\ (Pa) = 100 \times 6.112 \times \exp\left((17.67 \times T) / (T + 243.5)\right) \quad (1)$$

$$\text{(Partial) Vapour Pressure } Pw\ (Pa) = RH \times \text{Saturated Vapour Pressure} / 100 \quad (2)$$

$$\text{Dew Point Temperature } (°C) = 4030 / (18.689 - \ln(Pw/133)) - 235 \quad (3)$$

Colder sheathing results in higher vapour condensation potential when there is air leakage from the indoor humid space. Being consistent with the discussion in section 5.2.3.1, Figure 19 shows that wall assemblies No. 1 and No. 2, both deep-cavity walls without exterior insulation, have very high potential of vapour condensation, which could occur about 40% of the year for a north-facing wall, if there is air leakage. The condensation potential is the highest in the winter when the sheathing is colder. Facing south reduces the risk. By comparison, the split-insulated walls No. 3-No. 6, all having exterior insulation to keep the OSB sheathing warmer, have greatly reduced vapour condensation potential (10-20% on a yearly basis). Wall No. 4 has slightly higher potential due to the lower R-value of the XPS (R5) insulation, compared to walls No. 3, No. 5, and No. 6, all with R6 exterior insulation.

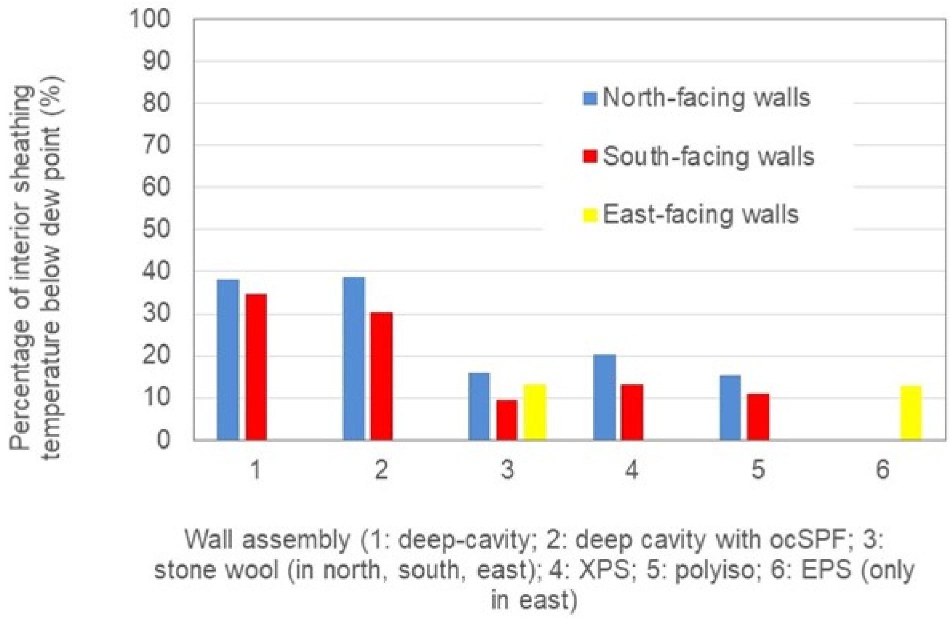


Figure 19. Percentages of the interior surface temperature of the OSB sheathing falling below the dew point for six wall assemblies in three orientations over the year of 2019

5.2.3.3 Effect of Exterior Insulation on Service Humidity of OSB Sheathing

The warmer temperature achieved by applying exterior insulation makes the OSB's ambient environment drier, which is subsequently expected to improve durability. Examining the test wall panels N1 and N3, the RH2 measurements from N3's OSB sheathing are lower than those of wall panel N1, by up to 15% in the winter (Figure 20). The major difference between wall panels N1 and N3 is N1 is a deep-cavity wall without exterior insulation, while N3 is exterior-insulated with vapour-permeable stone wool rigid insulation. Both walls have an interior poly vapour barrier to minimize outward vapour diffusion from the interior environment.

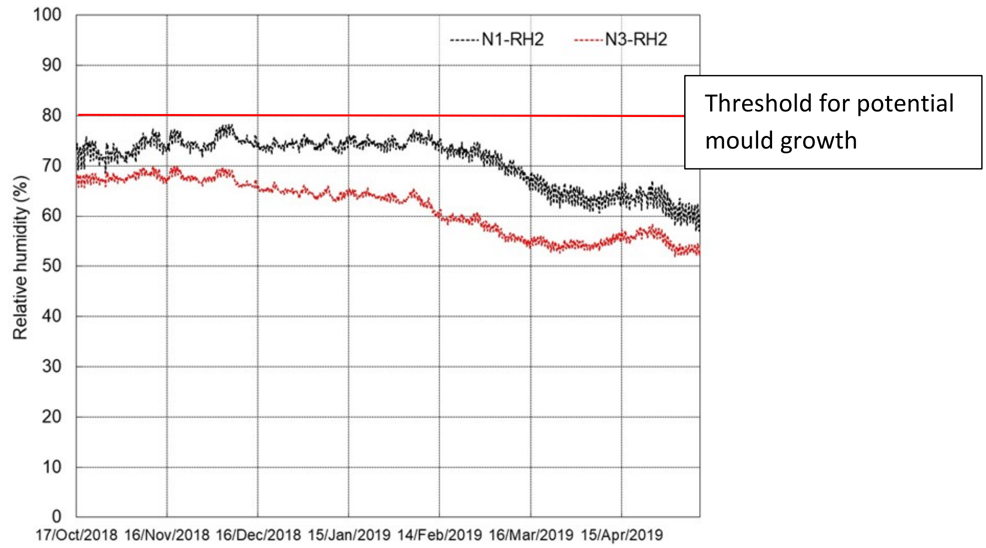


Figure 20. Relative humidity (RH2) on the interior surface of the OSB sheathing of north-facing test wall panels N1 and N3 (stone wool) over the first winter

Comparing test wall panel N4 (with XPS exterior insulation) to N3 (with stone wool) (Figure 21), it appears that the reductions in the RH2 measurements in N4 are considerably smaller than those in N3, both relative to wall panel N1 (without exterior insulation) over the winter season. Because all these three walls have the same interior poly vapour barrier, the difference is due to the presence and the permeability of the exterior insulation used. This result indicates that the stone wool exterior insulation in wall panel N3, allowing vapour to diffuse towards the exterior environment (i.e., the rainscreen cavity), provides a drier service environment for the OSB sheathing, compared to the less vapour permeable XPS in panel N4.

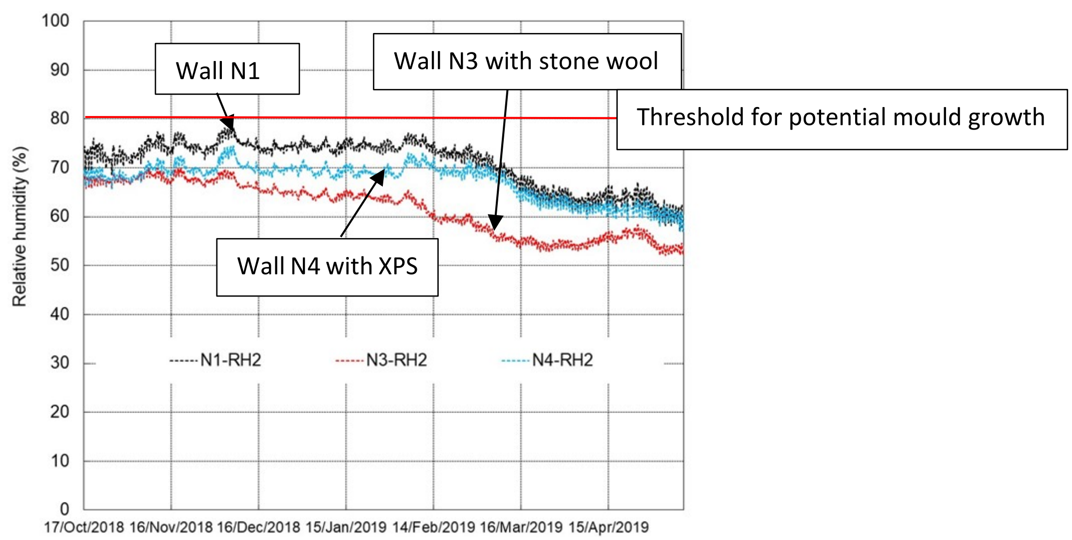


Figure 21. Relative humidity (RH2) on the interior surface of the OSB sheathing of north-facing test wall panels N1, N3 (stone wool) and N4 (XPS) over the first winter

5.2.4 Service Humidity of OSB Sheathing: Effect of Interior Vapour Control

As described in section 4.2, two types of interior vapour control methods, i.e., a poly vapour barrier (in wall assemblies No. 1, 3, 4, and 6) and vapour-retarding paints (in wall assemblies No. 2 and 5) are compared in this study. The vapour-retarding paints used in assemblies No. 2 and No. 5 are different products and applied to different materials (only on drywall for wall No. 5; for wall No. 2, the paint was initially just on ocSPF but later another paint was applied on the drywall). The painted drywall of wall No. 5 showed a vapour permeance of about 300 ng/(Pa·s·m^2) (vs. 500 ng/(Pa·s·m^2) of the drywall with regular paint) based on limited testing. The permeance of the two vapour-retarding paints applied on wall No. 2 are to be further assessed. Comparing the test wall panels of both deep-cavity wall assemblies facing the north, N1 and N2, the RH2 measurements from N1's OSB sheathing are much lower than those of wall panel N2 over the entire test period (Figure 22). The RH2 measurements from wall panel N1 remain below 80% over both winter seasons. Those from wall panel N2 stay above 90% over the first winter and mostly remain below 90%, but well above 80% over the second winter. This suggests that the OSB sheathing of wall panel N2 is susceptible to mould growth given the measured high humidity from its service environment. Compared to the RH2 readings from wall panel N1, the N2-RH2 levels are also much more sensitive to changes in the indoor environment, likely due to a lack of sufficient interior vapour control for the higher indoor RH. For example, the readings show a large spike, reaching 90% when the indoor RH jumped to 80% from late May to early June 2019. For wall assemblies No. 2 (i.e., test wall panels N2, S2), adding on November 26, 2019 a coat of another paint presumably[9] having a lower vapour permeance than the initial vapour-retarding paint sprayed on the ocSPF appears to slightly reduce the humidity level at the OSB sheathing. Relative to N1-RH2, the N2-RH2 readings are higher by over 15% in the first winter but reduce to approximately 10% over the second winter, not considering the variations in the interior and the exterior climatic conditions.

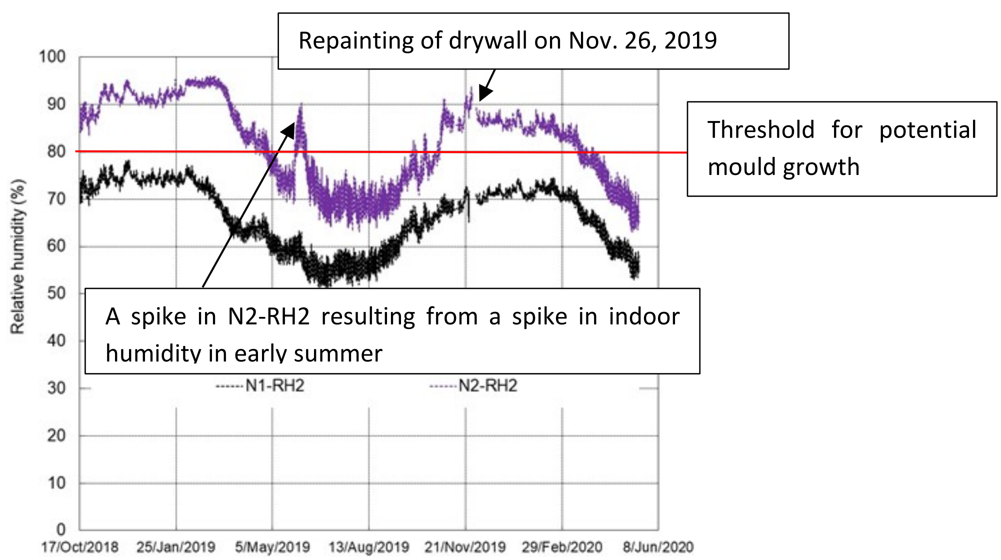


Figure 22. Relative humidity (RH2) on the interior surface of the OSB sheathing of north-facing test wall panels N1 and N2 over the entire test period

[9] It is called a "vapour barrier" paint by the manufacturer with its vapour permeance to be tested.

Among the north-facing split-insulated test wall panels (N3, N4, and N5), wall panel N5, which has an interior vapour-retarding paint applied on its drywall and an impermeable exterior insulation (i.e., foil-faced polyiso), shows the highest RH2 measurements over the entire test period (Figure 23). The N5-RH2 measurements consistently stay above 80% over the two winter seasons, suggesting high potential for mould growth. Similar to the N2-RH2 measurements, the N5-RH2 levels are also highly sensitive, including a considerable spike in early June 2019 due to a humidity increase in the indoor environment before turning off of the humidifier, compared to wall panels N3 and N4, both having an interior poly vapour barrier. The N4-RH2 measurements from test wall panel N4 remain below 80%. They are higher than those of wall panel N3 in the winter but similar to or even slightly lower than those of wall panel N3 in the summer. These differences are believed to be caused by differences in the vapour permeance between their exterior insulation products. The highly vapour-permeable stone wool exterior insulation of N3 better facilitates drying towards the exterior during the heating seasons. But under warm and damp weather conditions, which are not typical of Vancouver, the lower vapour permeance of XPS may reduce inward vapour drive from the exterior through the siding and the rainscreen cavity. See detailed analysis of vapour diffusion in section 5.4.

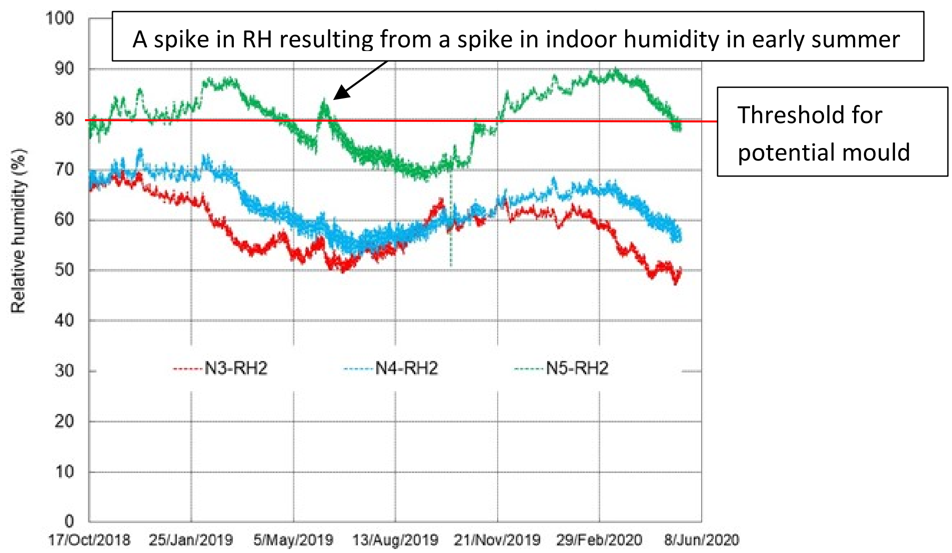


Figure 23. Relative humidity (RH2) on the interior surface of the OSB sheathing of north-facing test wall panels N3, N4 and N5 over the entire test period

5.2.5 Service Humidity of OSB Sheathing: A Summary of 12 Test Wall Panels

Figure 24, Figure 25, and Figure 26 provide a complete picture of the service environment of the OSB sheathing of all these 12 test wall panels. Among the five north-facing test wall panels (Figure 24), wall panel N2 overall shows the highest humidity levels on the interior surface of the OSB sheathing, followed by wall panel N5. The RH2 levels from these two walls consistently remain above 80% in the two winter seasons, indicating a high risk of mould growth on the sheathing. It also implies the interior vapour-retarding paint(s) used are not able to effectively prevent outward vapour diffusion from the humid indoor space. By comparison, wall panels N1, N3, and N4 show better performance, with their RH2 measurements consistently staying below 80% over the entire test period. Among these three wall panels, N3 overall shows the lowest humidity close to the OSB sheathing, wall panel N1 has the highest RH levels, and wall panel N4 is between N3 and N1.

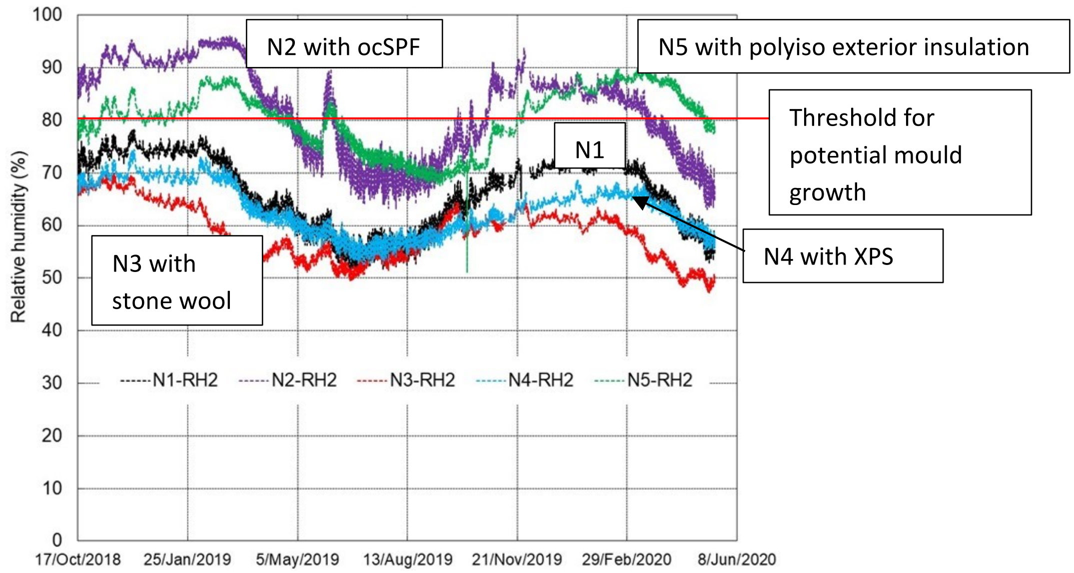


Figure 24. Comparison of the relative humidity on the interior surface of the OSB sheathing of five north-facing wall panels N1, N2 (ocSPF), N3 (stone wool), N4 (XPS), and N5 (polyiso) over the entire test period

The RH2 measurements from the five south-facing wall panels overall follow similar trends observed from the counterpart north-facing wall panels (Figure 25). But the measurements have much larger fluctuations, as expected, particularly in wall panels S1 and S2, where the OSB sheathings are not covered by exterior insulation and thus more exposed to the exterior environment. Overall, the south-facing wall panels are drier than the corresponding north-facing wall panels. The two east-facing wall panels E1 (wall assembly No. 3) and E2 (wall assembly No. 6) are very close in terms of the RH2 measurements at the interior surface of the OSB sheathing (Figure 26). The EPS exterior insulation in wall panel E2 has much lower vapour permeance than the stone wool exterior insulation used in wall panel E1 but is more permeable than XPS. Among the four exterior insulation products covered in this study, the Canadian building code only considers foil-faced polyiso to be a vapour barrier material. Foil-faced polyiso has a dry cup vapour permeance close to zero (see material properties in Appendix I, Table 4, ASTM 2010).

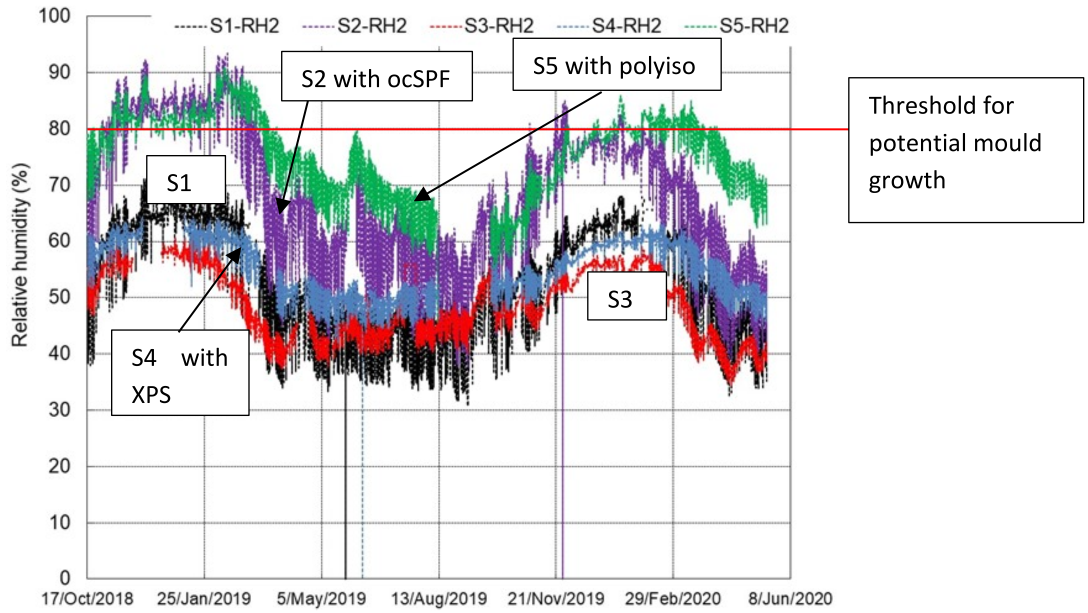


Figure 25. **Comparison of the relative humidity on the interior surface of OSB sheathing of five five-facing wall panels S1, S2 (ocSPF), S3 (stone wool), S4 (XPS), and S5 (polyiso) over the entire test period**

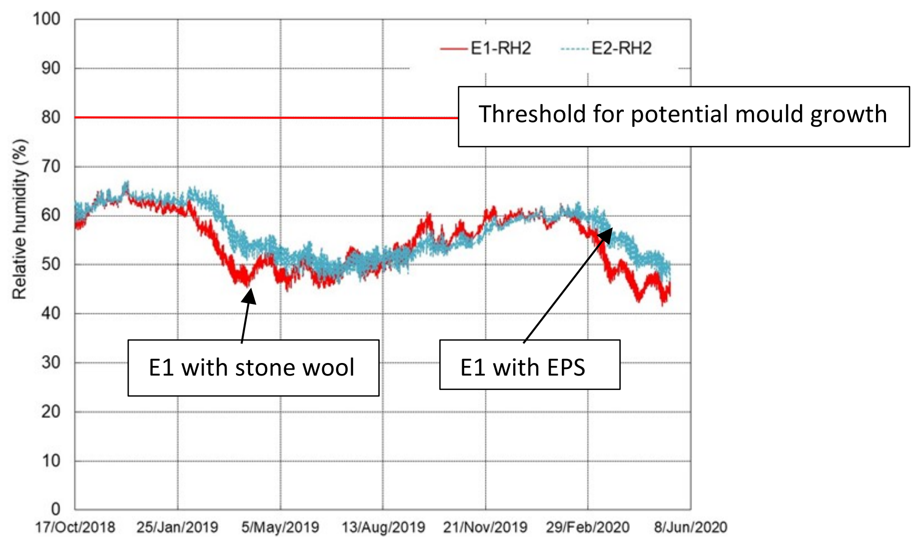


Figure 26. **Comparison of the relative humidity on the interior surface of OSB sheathing of two east-facing wall panels E1 (stone wool) and E2 (EPS) over the entire test period**

To summarize, both the interior vapour control method and the type of exterior insulation used in these six types of wall assemblies show impacts on the service environment of the OSB sheathing. It appears that the OSB sheathings of wall No. 1, No. 3, No. 4, and No. 6, all with an interior poly vapour barrier, are in a much drier service environment and should remain more durable; but wall No. 2 and No. 5, both with an interior vapour-retarding paint, show potential risk of mould growth on their sheathing due to the higher humidity levels in their service environment resulting from outward vapour diffusion.

5.3 Wood Moisture Content

The MC of wood provides more direct indication about the durability risk, since fungi including mould and decay all require a minimum MC to grow in wood, even when all other conditions, such as temperature and material (i.e., nutrients) are favourable (Morris 1998; FPL 2010). For example, in terms of decay, a study by FPInnovations showed that the MC of kiln-dried lumber, plywood, and OSB needed to rise to approximately 26% for decay fungi to initiate at the temperature of 20°C; it then took months at this MC level for detectable strength loss to occur (Wang et al. 2010). Mould may grow on the surface of damp wood, with a minimum RH of about 80% (Viitanen and Paajanen 1988; Nielsen 2004). A MC of 16%, being largely consistent with the 80% RH cited above (FPL 2010) for indicating mould growth potential, is used in the following sections as a criterion for assessing the impact of wall assembly design on durability performance of the OSB sheathing[10]. It is acknowledged that this criterion tends to be stringent compared to what may be found in the literature. Typically, a MC of 20% or higher has been used, when decay is a concern in other studies (e.g., Smegal et al. 2017).

For measuring MC of the OSB sheathing in this study, the uninsulated moisture pins are installed from the interior surface to the mid-depth (about 6 mm) to avoid direct impact of liquid water during intentional water injections on the measurements, not representing sheathing's true MC[11]. Such a measurement method is expected to be more sensitive to interior wetting and to report the highest MC in the inner half of the OSB sheathing. When the exterior surface of the OSB sheathing is wet due to water injection or localized vapour condensation, it will take time to detect, with the measurements tending to lower the magnitude in MC changes, compared to those at the exterior thin surface. Examining the responses of the test walls to the three phases of water injection, it is found that the delay is about 1-2 days for the MC measurements to show elevation after start of each phase of water injection. This should be the time for the water first to transfer from the wetting pad to the OSB, and then distribute through the exterior half (in thickness) of the OSB sheathing. See more information about measuring wood MC in Appendix X.

5.3.1 Moisture Content Profiles of Wall Studs and OSB Sheathing

Wall assemblies No. 3 and No. 5 are taken as examples in this section to provide a range of MC profiles for the six wall assemblies tested in this study. Figure 27, Figure 28, and Figure 29 show the MC profiles measured from both the OSB sheathing and the wall studs of wall assembly No. 3 with stone wool exterior insulation, including north-facing wall panel N3, south-facing S3, and east-facing E1. Note 11.4% is the lower limit of measurements for the wall studs, with the calibration based on white spruce, and 8.2% is the lower limit of measurement for the OSB sheathing. The difference in these two lower limits is expected to be primarily caused by the resin in OSB. MC below the lower limit could not be accurately measured by the resistance-based measurement method. Obviously, the wall studs are very dry, with the MC readings typically below or just marginally above the lower limit of the measurement during the entire test. The OSB's MC shows a similar trend, until water was injected into the wetting pad installed on its exterior surface. Overall, both the wall studs and the sheathing of wall assembly No. 3 remain

[10] As with any study, each MC measurement will be at a single point in the assembly. How this translates to actual performance in the field will depend on the variability in MC throughout the assembly or wall component, as well as variability in the actual decay potential of the material. Because this study is focused on how the relative responses of different wall assemblies respond to changes to the environmental conditions and accidental wetting, having the precise MC at which decay occurs is not critical.

[11] There are always moisture gradients inside wood when its surface is exposed to a wetting source, with the exposed surface wetting up quickly but the remaining needing time to respond. In this study, it is important to note that the source of liquid water is anticipated to primarily come from the exterior side of the OSB sheathing through intentional water injection. Directly measuring MC of the exterior surface when water is injected will not reflect the real MC, particularly of the remaining wood.

dry, showing little seasonal effect. The wall design provides the OSB sheathing with a good drying capacity; its MC drops quickly and mostly remains below 16% after each phase of water injection.

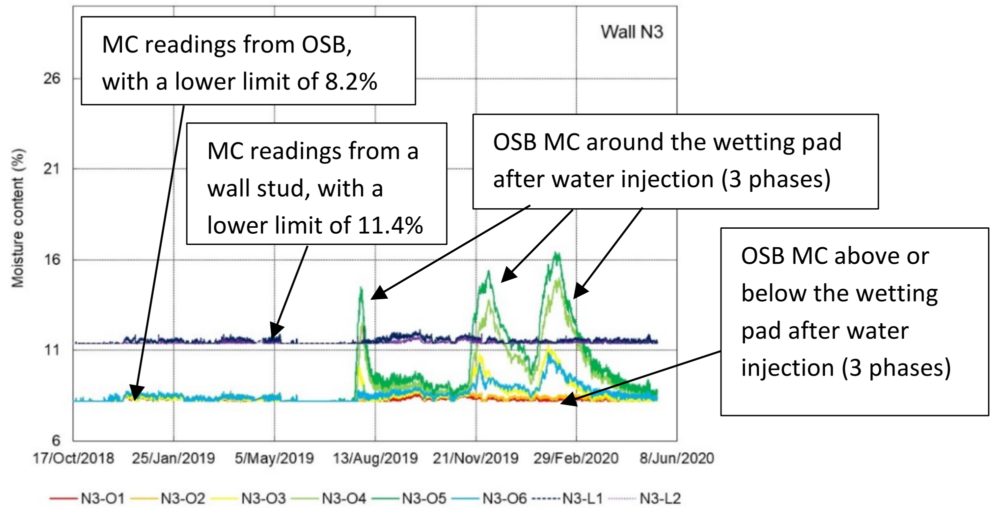


Figure 27. **Moisture content measured from the OSB sheathing (O1-O6) and a wall stud (L1, L2) of north-facing wall No. 3 (wall panel N3) with stone wool exterior insulation**

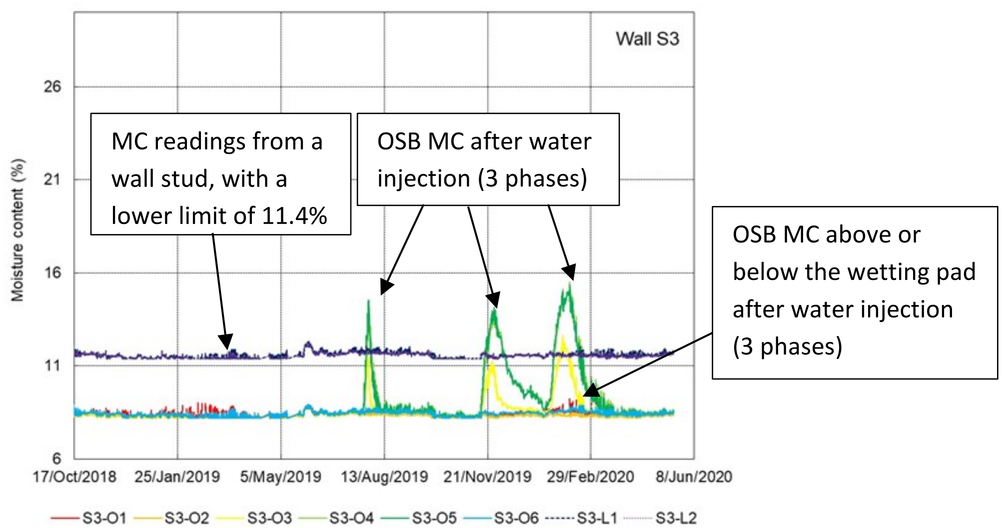


Figure 28. **Moisture content measured from the OSB sheathing (O1-O6) and a wall stud (L1, L2) of south-facing wall No. 3 (wall panel S3) with stone wool exterior insulation**

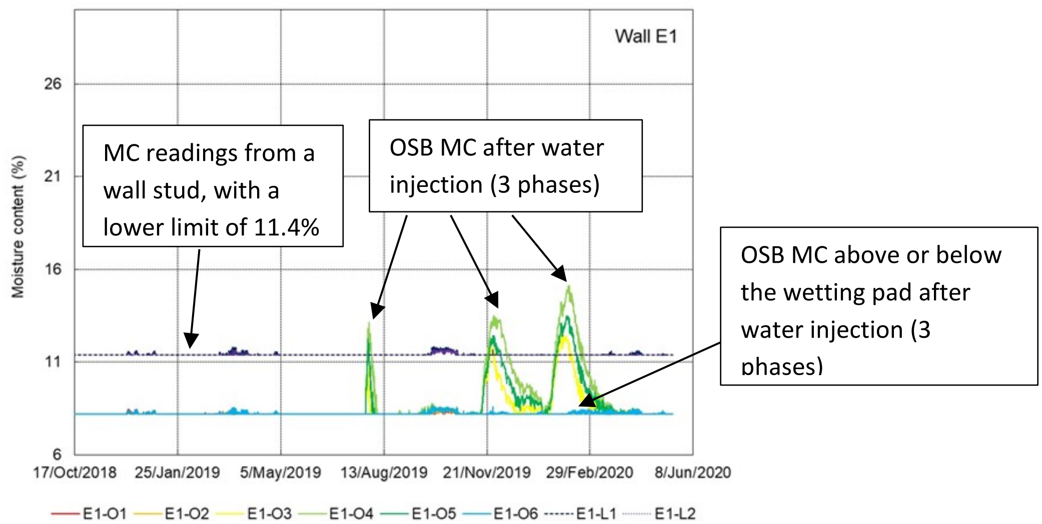


Figure 29. Moisture content measured from the OSB sheathing (O1-O6) and a wall stud (L1, L2) of east-facing wall No. 3 (wall panel E1) with stone wool exterior insulation

Compared to wall assembly No. 3, wall assembly No. 5 (with foil-faced polyiso exterior insulation), particularly its north-facing wall panel N5 responds less favourably to both seasonal environmental changes and water injection. Examining Figure 30, the N5-L1 MC measurements (i.e., from a stud at a measurement location close to the OSB sheathing of wall panel N5) clearly show moisture accumulation over the winter, with peak MC occurring in late spring and early summer and exceeding 16%, indicating a high level of humidity in its service environment. This is consistent with the high RH measurements from this wall (section 5.2.5). As expected, the measurements from the same wall stud but at a location close to the indoor space (i.e., N5-L2) are lower, being about or slightly over 12%. This MC mostly reflects the indoor environment since only the drywall painted with a vapour-retarding paint separates them.

The MC measured from wall panel N5's OSB sheathing also shows seasonal elevations. It exceeds 16% in late spring and early summer for short periods of time when there is no water injection, or when it is measured at points (e.g., measurement points N5-O1 and N5-O2) well away from the water injection area. This wall panel's OSB sheathing responds relatively poorly to water injection. The peak MC measurements from the wetting area (i.e., N5-O5) exceed 22% after phase A water injection in late July. In the warm weather, the sheathing dries out, most likely due to moisture movement towards the interior. The MC drops below 16% within approximately five weeks. However, after phases B and C of water injection, the MC measurements at or below the wetting area plateaued at around 18% MC. There was some difficulty in injecting water into this wall panel during these two phases; consequently, much smaller amounts of water are expected to have reached N5's OSB sheathing, compared to the other wall panels[12]. Otherwise, the MC would be expected to plateau at a much higher level. With vapour diffusing generally towards the exterior in cold weather, drying towards the exterior is restricted in N5 due to the impermeable exterior insulation. The charts (Figure 30; Figure 31) of wall assembly No. 5 also indicate that water runs down quickly after each water injection, based on the elevated MC measurements from the area below the wetting pad (i.e., N5-O6), being close to the three MC measurement points (N5-O3, N5-O4,

[12] There was no obvious reason why the water injection became difficult. When the wall assembly was removed, there was still no clear explanation for the difficulties in injecting water into the N5 wetting pad.

and N5-O5) located at the top edge, mid-point, and bottom edge of the wetting area, respectively. This retention and distribution of moisture is likely attributed to the rigid and impermeable nature of the exterior insulation panel, which prevents drying once water enters the space between the OSB and the exterior insulation. To summarize for wall assembly No. 5, the MC measurements imply high moisture risk. This is likely caused by both the uncontrolled outward vapour diffusion from the indoor space due to a lack of an effective interior vapour barrier or retarder and the poor drying towards the exterior due to the impermeable exterior insulation used.

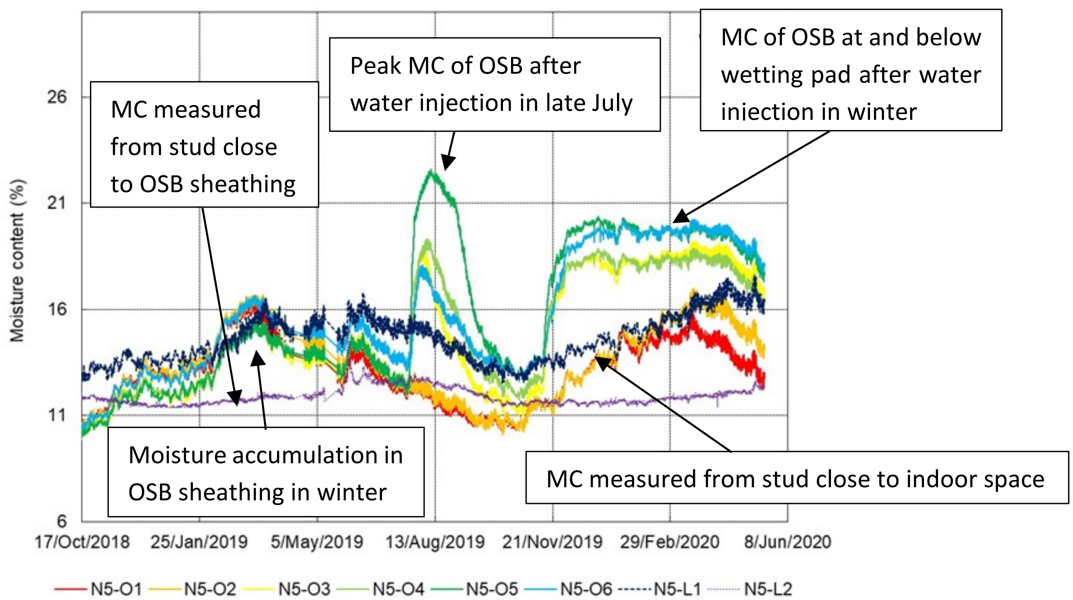


Figure 30. Moisture content measured from the OSB sheathing (O1-O6) and a wall stud (L1, L2) of north-facing wall No. 5 (wall panel N5) with foil-faced polyiso exterior insulation

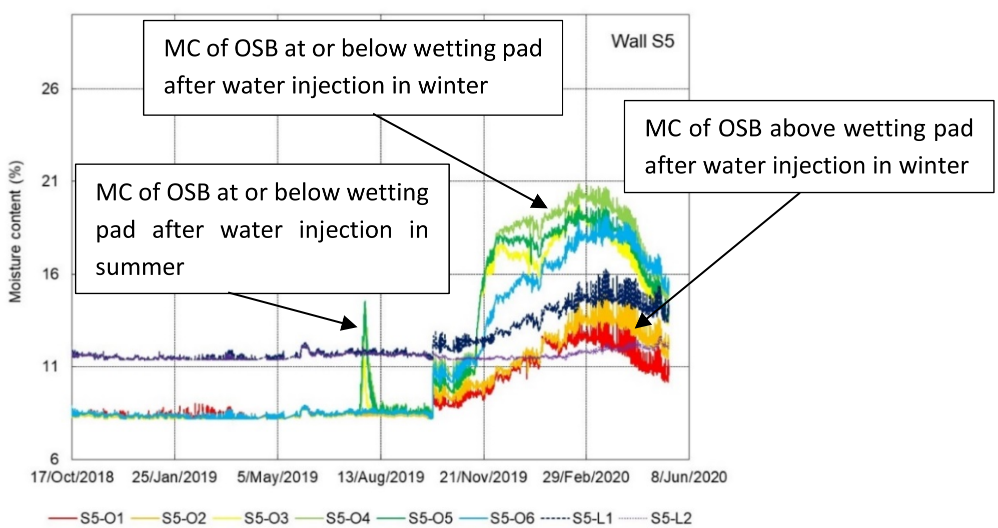


Figure 31. Moisture content measured from the OSB sheathing (O1-O6) and a wall stud (L1, L2) of south-facing wall No. 5 (wall panel S5) with foil-faced polyiso exterior insulation

To summarize, the five charts (Figure 27-Figure 31) shown above provide general trends that: 1) the north-facing walls have higher MC than the corresponding south-facing walls; and 2) compared to wall studs, the OSB sheathing responds more poorly to moisture resulting from seasonal changes and water injection. Therefore, MC measurements from the OSB sheathing of the north-facing test wall panels, except for wall assembly No. 6 with its only east-facing wall panel E2, are focused on in the next sections to assess the walls' wetting and drying behaviour. In terms of the three MC measurements (O3, O4, and O5) from the OSB's wetting area, there are noticeable height-dependant variations. The lower spots (e.g., O4, O5) tend to have higher MC readings, resulting from water running down during water injection and the lower spots subsequently remaining wet longer. An average MC based on these three measurements, labeled as "OSB" in the charts below, is used to show the impact of water injection and the subsequent drying. It also appears that the water flow surpasses the wetting pad in most walls, which is detected by an increase in the MC levels measured at O6 located below the wetting pad. This phenomenon is most obvious in wall assembly No. 5, followed by No. 4. These two walls both have a rigid exterior insulation layer that tends to compress the wetting pad, and to slow drying towards the exterior because of its lower vapour permeance.

5.3.2 Wetting and Drying Behaviour of OSB Sheathing

5.3.2.1 Test Wall panel N1, Deep-Stud Wall with Poly

The OSB sheathing of test wall panel N1 has MC readings just slightly above 11% in the winter seasons; during this period, there was no water injection (Figure 32). The MC measurements from the sheathing at different heights are consistent, with the lower spots (e.g., N1-O6) showing slightly higher measurements than the higher locations (e.g., N1-O1). The average peak MC measurements after each phase of water injection remain below 16%. The wall shows good drying performance following water injection in both summertime and wintertime, indicating an acceptable level of tolerance against elevated exterior moisture loads, typically caused by rain penetration in field. This wall dries towards the exterior, with an interior poly vapour barrier in place. The test shows this deep-stud wall assembly does not have a large durability concern in the Vancouver climate when it is built airtight.

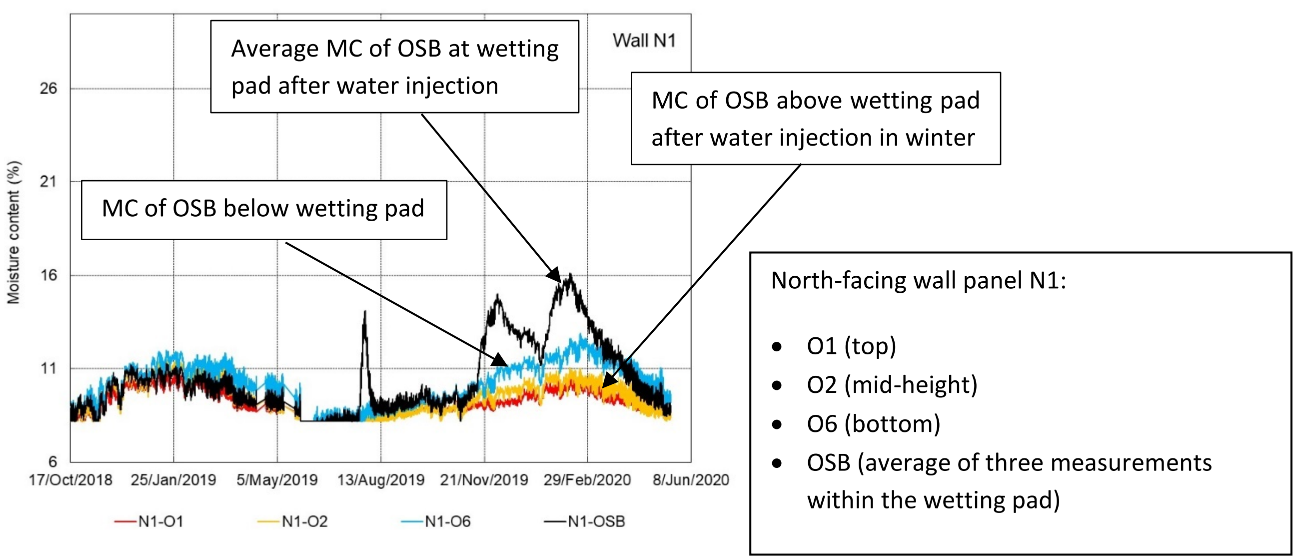


Figure 32. Moisture content measured from the OSB sheathing of north-facing wall panel N1

5.3.2.2 Wall Assembly No. 2, Deep-Stud Wall with Open-Cell Spray Foam and Vapour-Retarding Paint

The measurements from the OSB sheathing of test wall panel N2 show moisture accumulation in wintertime. The MC persistently stays above 16%, reaching a peak of 19% in mid-March after the first winter and prior to the start of any water injection (Figure 33). This must be primarily caused by outward vapour diffusion in a heating season, which is consistent with the high RH measurements from this wall, as discussed in section 5.2. By comparison, the overall MC measurements in the second winter, ignoring the two peaks in MC following phases B and C of water injection, are generally lower. It appears the major contributing factor to this change should be the reduced interior vapour permeance after its drywall being refinished with a vapour-retarding paint on November 26, 2019.

The OSB sheathing of this wall panel quickly dries starting in late March after reaching the peak MC over the first winter; its MC reduces to about 10% in early June. During the three phases of water injection, the peak MC measurements all slightly exceed 16%, followed by quick drying. Without any vapour barrier material on either side, this wall can dry both inwards and outwards when environmental conditions allow. Compared to the north-facing wall, the south-facing wall panel S2 is drier and has better performance over the entire test period (Figure 34).

The study indicates that this deep-stud wall assembly is likely to show mould growth in the field when the indoor environment has relatively high humidity levels. The high chance for its sheathing's temperature to fall below the dew point further increases the risk (as discussed at 5.2.3.2). This moisture risk is higher at locations, such as in a north orientation with limited exposure to solar radiation. The concern has been previously reported, mostly based on laboratory and field testing about similar applications of ocSPF in unvented wood-frame roof systems (Smegal et al. 2017). Installing a more impermeable vapour control layer, for example, an effective vapour barrier (with vapour permeance below 60 ng/(Pa·s·m^2)) should improve the performance to address this concern. More detailed specifications will be further investigated based on material characterization and hygrothermal modelling at the next step.

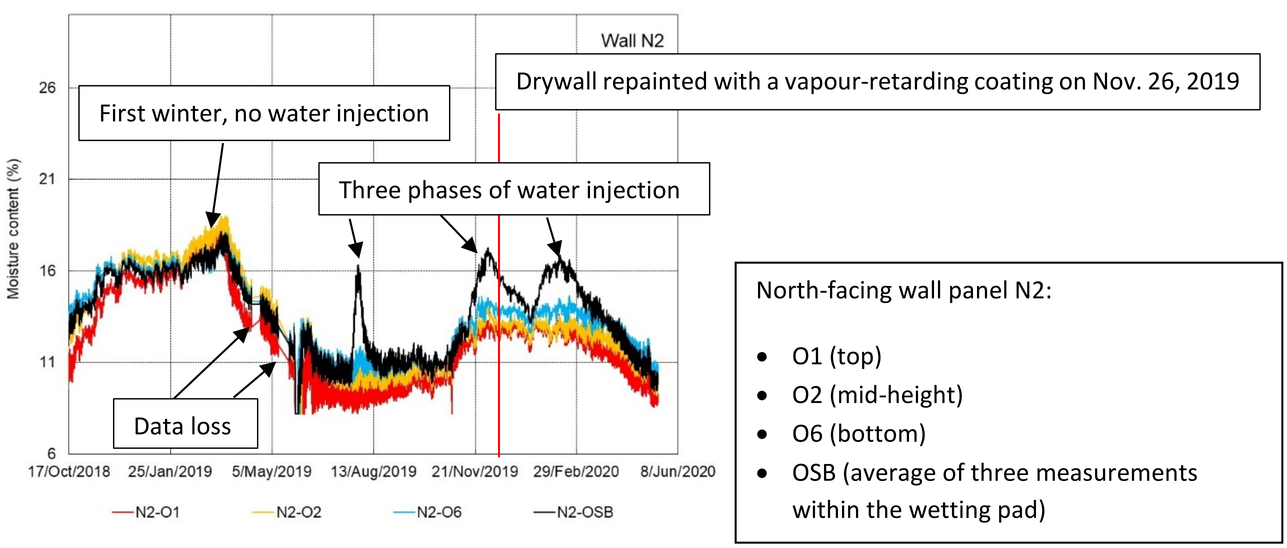


Figure 33. Moisture content measured from the OSB sheathing of north-facing wall panel N2

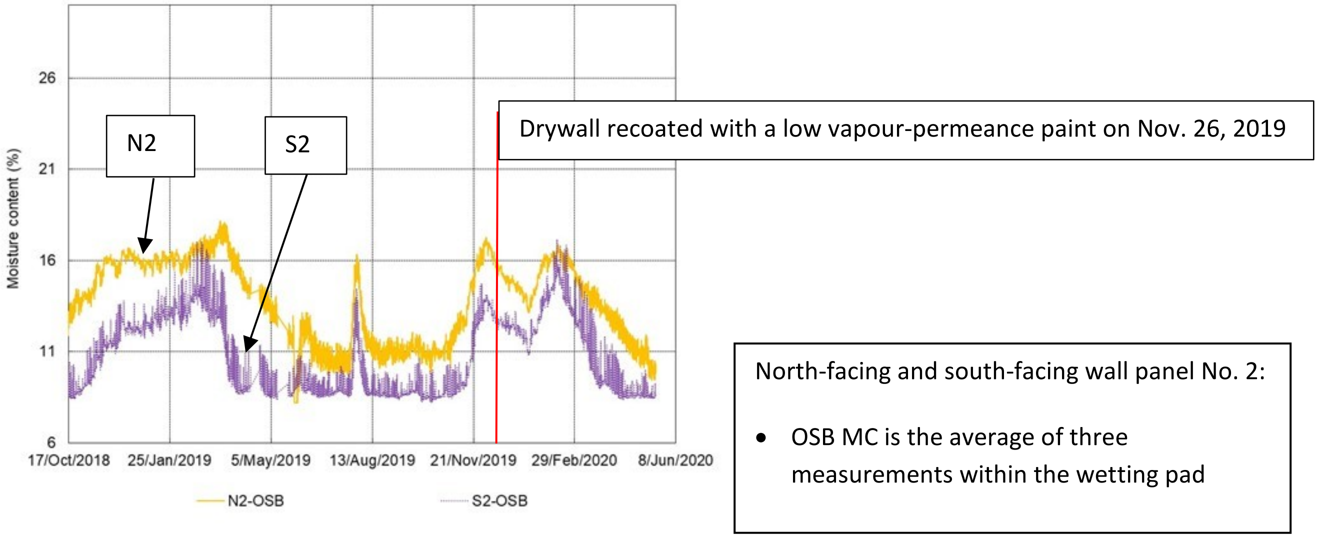


Figure 34. Moisture content measured from the OSB sheathing of north-facing wall panel N2 and its south-facing counterpart S2

5.3.2.3 <u>Test Wall Panel N3, with Stone Wool Exterior Insulation and Poly</u>

As discussed in section 5.3.1, test wall panel N3 remains dry throughout the test. The three peak MC readings all remain below 14%, followed by quick drying after each phase of water injection (Figure 35). With the interior poly vapour barrier to prevent wetting from the high indoor humidity and the highly vapour-permeable stone wool exterior insulation to facilitate drying towards the exterior, this wall is expected to be durable and tolerant of extra moisture in building service.

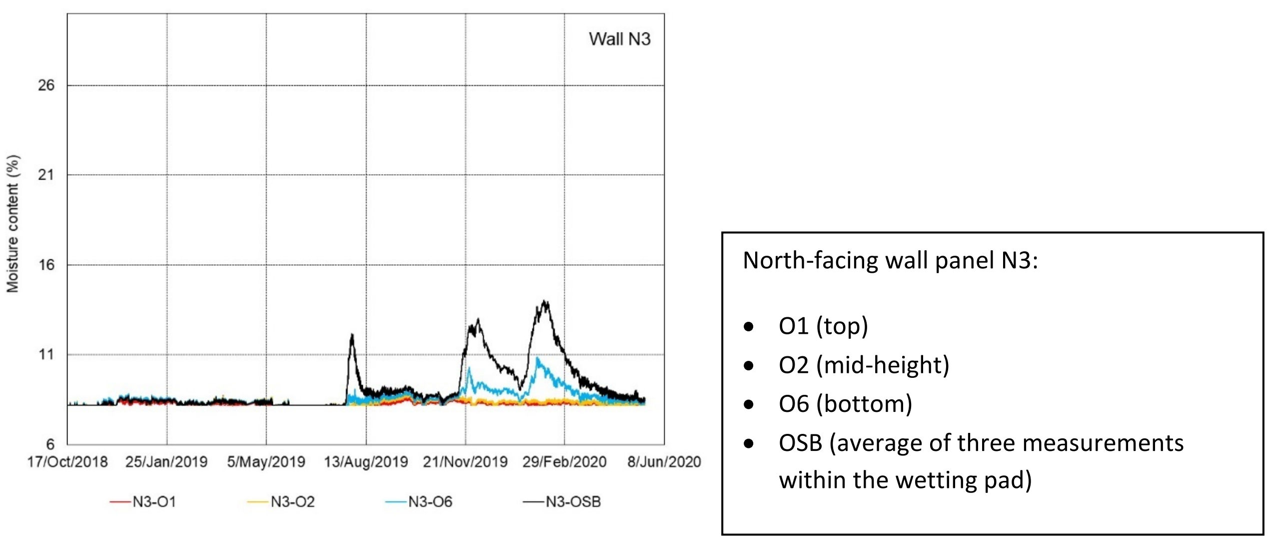


Figure 35. Moisture content measured from the OSB sheathing of north-facing wall panel N3 with stone wool exterior insulation

5.3.2.4 <u>Test Wall Panel N4, with XPS Exterior Insulation and Poly</u>

Test wall panel N4 also shows acceptable performance during this test (Figure 36). When there is no water injection, the OSB sheathing's MC (i.e., N4-O1, N4-O2) remains low, below 10% throughout the year. The average MC measurements from the wetting area (i.e., N4-OSB), slightly exceed 16% after each phase of water injection.

The wall shows acceptable drying performance; the drying certainly takes longer with lower drying rates in the winter, compared to the summer. With a poly interior vapour barrier in place, the drying of this wall can occur towards the exterior, i.e., through the XPS. The 1 in. thick XPS used in this wall has a vapour permeance, according to the manufacturer, of about 87 ng/(Pa•s•m²) (about 1.5 US perm) (Appendix I). It is therefore not a vapour barrier material and allows some vapour diffusion. The Canadian building codes define a vapour barrier to be a material with a dry cup vapour permeance below 60 ng/(Pa•s•m²) (NRC 2015). But compared to the stone wool exterior insulation used in wall No. 3, the much less permeable XPS greatly reduces the drying capacity towards the exterior.

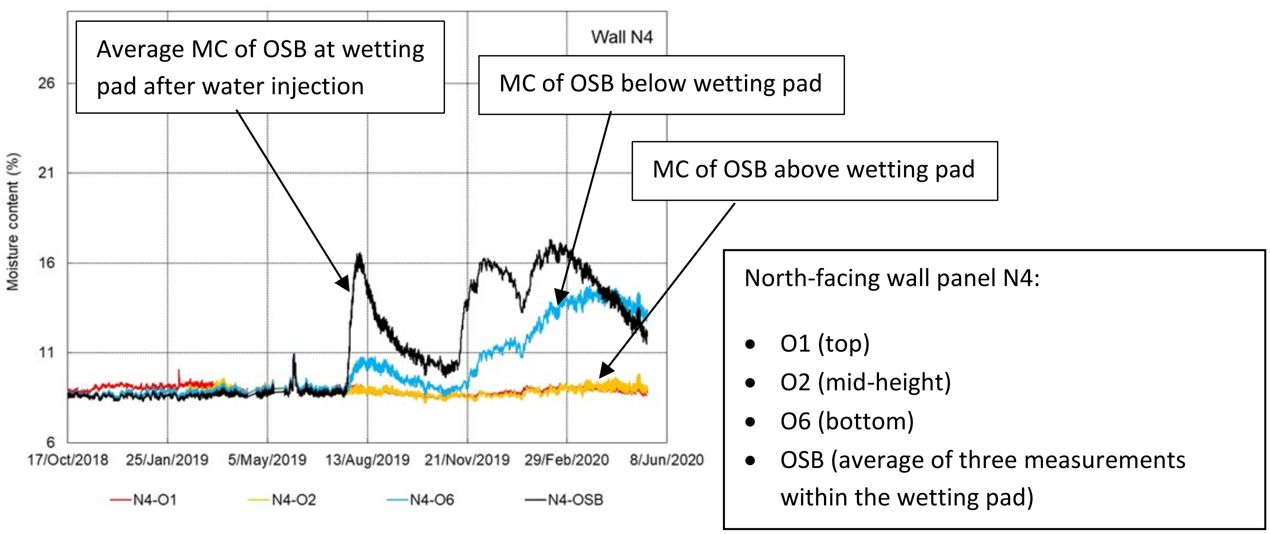


Figure 36. Moisture content measured from the OSB sheathing of north-facing wall panel N4 with XPS exterior insulation

5.3.2.5 Wall Assembly No. 5, with Foil Faced-Polyiso Exterior Insulation and Vapour-Retarding Paint

As discussed in section 5.3.1, wall assembly No. 5 with vapour-impermeable foil-faced polyiso exterior insulation (with vapour permeance close to 0) has potential durability risk, based on this test (Figure 37; Figure 38). The MC measurements from its OSB sheathing (i.e., N5-O1, N5-O2) reach 16% in the winter in the north-facing wall panel N5 before the start of water injection. When water was injected in July 2019, the average MC of the wetting area (i.e., N5-OSB) reaches about 20% but dries within about two months under the summer environmental conditions. The MC again reaches around 20% but remains stable after the water injection in phase B in November 2019. The water injection in phase C does not considerably increase the MC beyond 20%. These MC readings would likely have been higher if no difficulties were encountered in injecting water during these two phases[13]. The peak MC of this wall does not decrease until the warmer periods during the following summer. Compared to the north-facing wall panel N5, its south-facing wall panel S5 shows less severe wetting and also dries faster in the summer (Figure 38). In colder seasons, its peak MC reaches 18% when water was injected in November; it further increases to about 20%, following phase C water injection in January 2020. It again shows faster drying than the north-facing wall panel N5 when the weather becomes warmer in March 2020.

[13] Due to difficulties in injecting water onto the N5 wetting pad in phases B and C, the amounts of water injected onto N5 was considerably less than those for other test wall panels in November 2019 and January 2020.

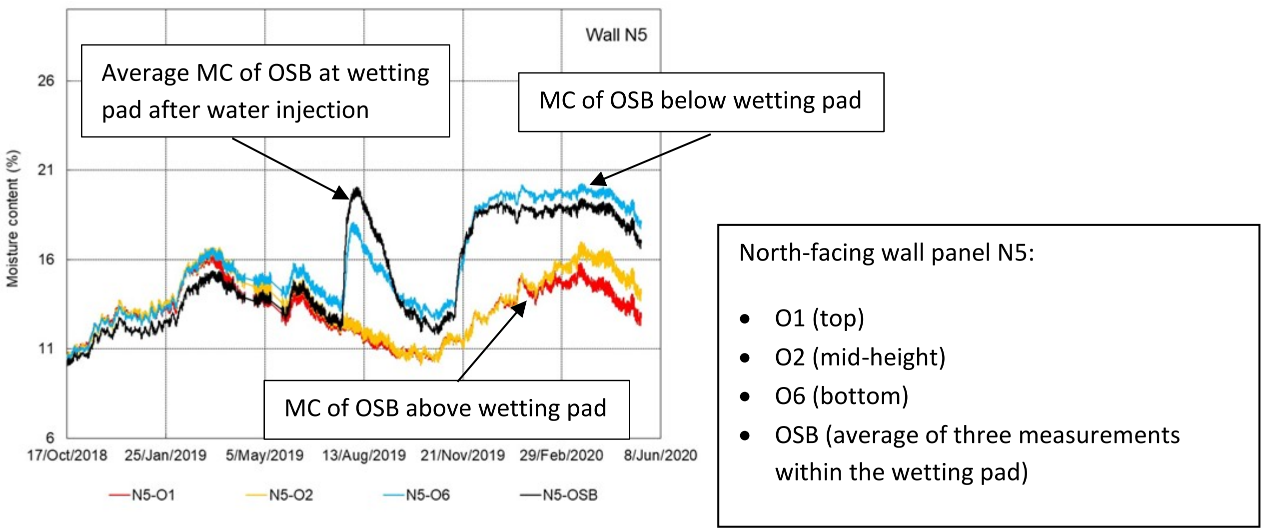


Figure 37. Moisture content measured from the OSB sheathing of north-facing wall panel N5 with foil faced-polyiso exterior insulation

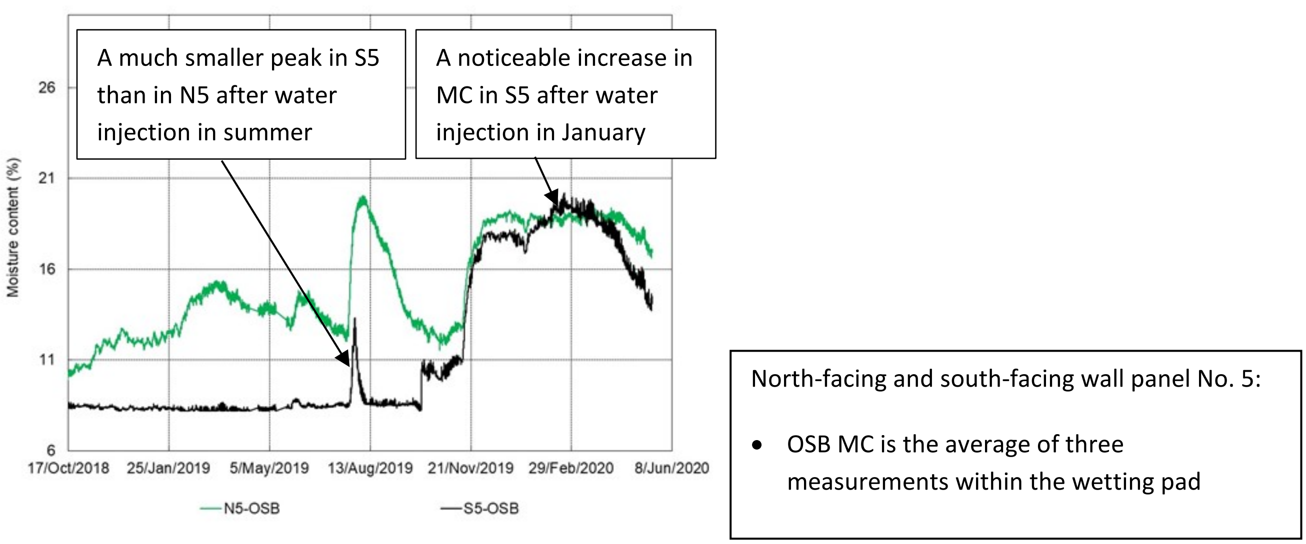


Figure 38. Moisture content measured from the OSB sheathing of north-facing wall panel N5 and south-facing wall panel S5 with foil faced-polyiso exterior insulation

5.3.2.6 Test Wall Panel E2, with EPS Exterior Insulation and Poly

Test wall assembly No. 6, i.e., the east-facing wall panel E2 with EPS exterior insulation shows good performance (Figure 39). EPS is known to be reasonably vapour permeable, with a dry cup vapour permeance about 130 ng/(Pa•s•m²) (about 2 US perm) (Appendix I). Prior to start of the water injection, its sheathing's MC (i.e., E2-O2 at mid-height) mostly remains below the lower measurement limit, i.e., 8.2% throughout the test. The three phases of water injections raise the MC (i.e., E2-OSB) in both the summer and the winter, with the peak MC reaching 16% in the winter. However, the wall dries out reasonably quickly. Interestingly, its E2-O1 measurement location, i.e., at the upper portion of the OSB sheathing shows slightly elevated MC on a few occasions over the winter. This could be caused by minor rain penetration, with the east orientation receiving the most severe wind-driven rain during the rainy winter months in Vancouver.

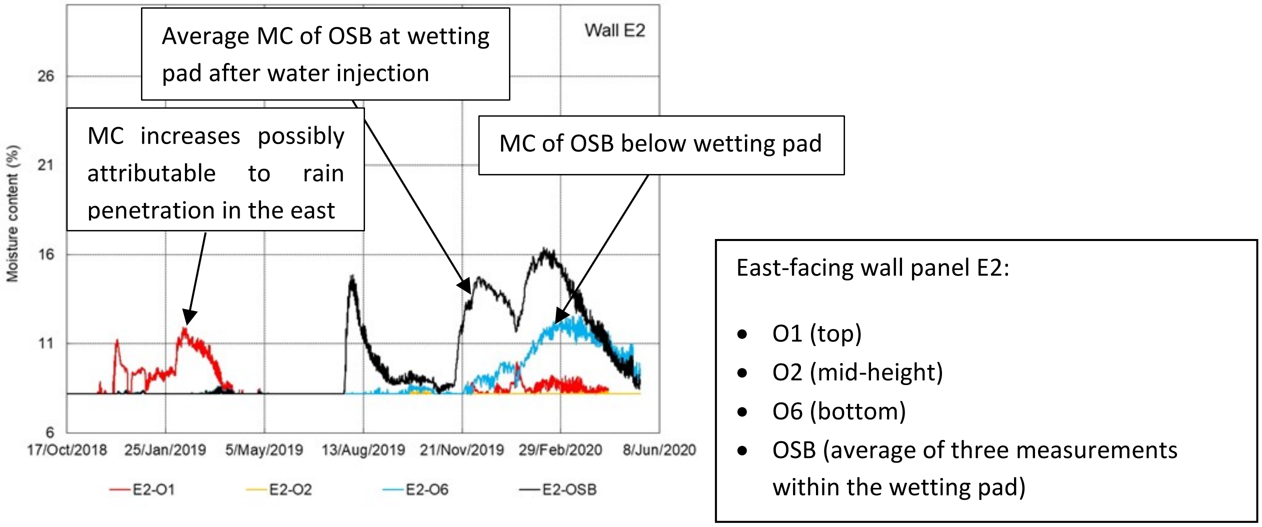
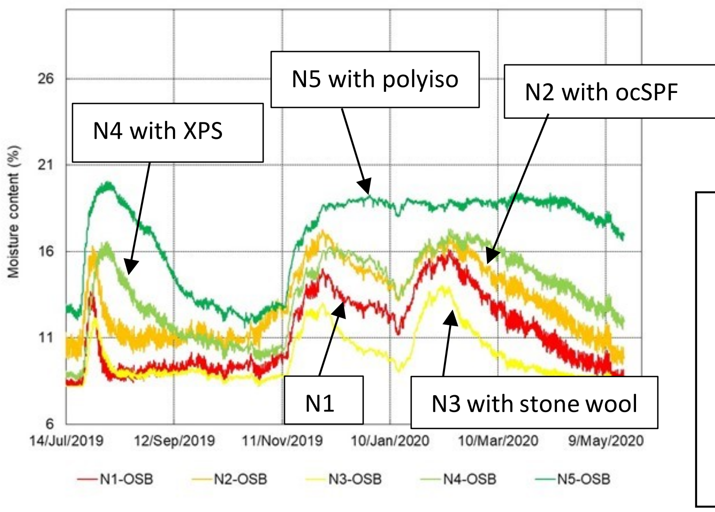


Figure 39. Moisture content measured from the OSB sheathing of east-facing wall panel E2 with EPS exterior insulation

5.3.2.7 Comparison of Responses to Water Injection among Wall Assemblies

Comparing the five north-facing walls (Figure 40), test wall panels N3 (with stone wool exterior insulation), N1 (deep cavity without exterior insulation), N2 (deep cavity without exterior insulation), N4 (with XPS exterior insulation), and N5 (with foil faced-polyiso exterior insulation) have increasingly larger peaks in the average MC measurements from the wetting area following water injection. Wall No. 5 shows a major deficiency in drying capacity, as its MC remains at around 20% following the second and the third water injection events. Continuing the discussions in section 5.2 regarding potential mould growth based on the interstitial environmental conditions, Figure 40 suggests that if water is to find its way into the space between the impermeable exterior insulation and the OSB sheathing and be periodically replenished (e.g. due to a failure in the building envelope), wall assembly No. 5 will have a higher chance of supporting mould growth than wall assembly No. 2. Although fewer data are available for wall No. 6 (with EPS exterior insulation), the available MC data from the two wall panels E1 (i.e., wall assembly No. 3 with stone wool exterior insulation) and E2 (i.e., wall No. 6) in the east orientation (Figure 41) suggest that this wall will have a lower drying capacity than wall No. 3. However, wall No. 6 should have better drying performance than wall No. 4, as a result of the lower vapour permeance of the EPS, compared to XPS.

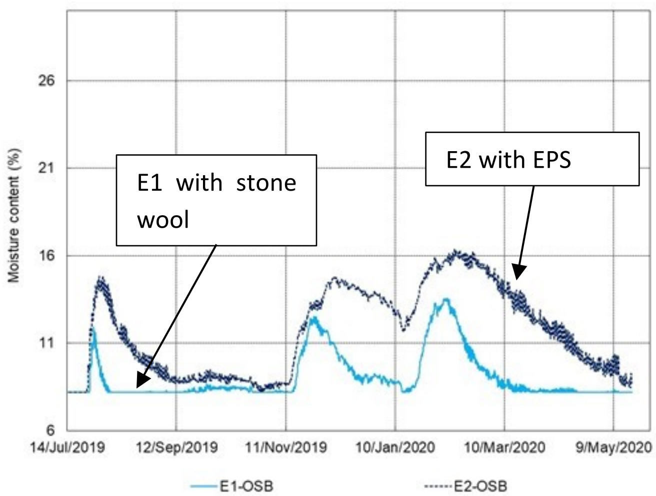


Water injection schedules:

- July 2019
- November 2019
- January 2020

MC based on the average of the three MC measured in each wetting area

Figure 40. Responses of the OSB sheathing to three phases of water of five north-facing wall panels



Water injection schedules:

- July 2019
- November 2019
- January 2020

MC based on the average of the three MC measured in each wetting area

Figure 41. Responses of the OSB sheathing to three phases of water injection of two east-facing wall panels E1 with stone wool and E2 with EPS exterior insulation

5.4 Vapour Diffusion Potential

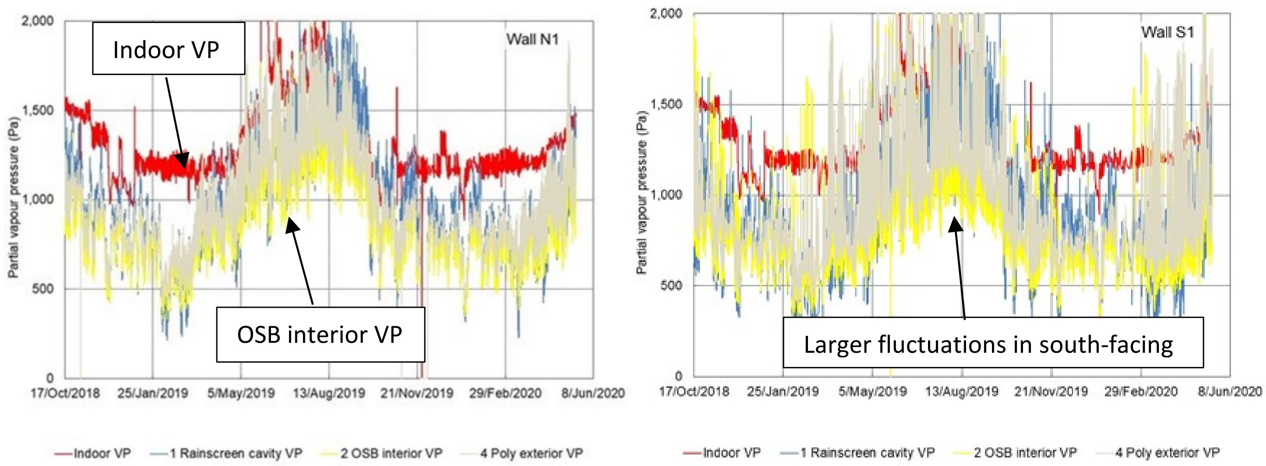
Vapour diffusion is expected to be a primary mechanism influencing the hygrothermal performance of the test walls in this study, since all walls are built to be airtight and watertight, except for the simulated water leaks through three phases of intentional water injection. As expected for a relatively cold climate such as Vancouver's, vapour drive (flow direction) is predominantly outward through the building envelope. Vapour movement under vapour pressure gradients could result in dissipation of water vapour from wood components (for example, causing the OSB sheathing of the test walls to accelerate its drying); or reversely cause the MC to rise due to increased humidity levels in the assembly or even vapour condensation if the local temperature drops below the dew point. Resistance to vapour flow plays an important role in both vapour drive and diffusion rates. That is why building envelope designs aim to select and arrange materials so that the vapour permeance aids in both reducing potential wetting and maximizing drying potential, associated with vapour flow; for example, vapour barriers and vapour retarders need to be selected and placed depending on the anticipated interior and exterior climatic conditions. A poly vapour barrier is traditionally used in Canadian climates as an interior vapour barrier/air barrier to minimize wetting caused by indoor warm and humid air; however, sheet polyethylene also stops drying towards the interior due to its impermeable nature, which is a disadvantage. A vapour retarder with a higher vapour permeance than 6 mil sheet polyethylene, typically a paint product applied on drywall etc. is increasingly specified when there is a desire to maintain some drying capacity towards the interior, particularly for an energy efficient building envelope system. Canadian building codes define a vapour barrier material as one with a dry cup vapour permeance below 60 ng/(Pa•s•m²) (about 1 US perm) (NRC 2015). There is no official definition for vapour retarders in Canadian codes; but it is commonly understood among building envelope engineers and architects that a material with vapour permeance in range of 60-600 ng/(Pa•s•m²) (about 1-10 US perm) would be acceptable; this is consistent with the Class III vapour retarders (i.e., the so-called vapour semi-permeable class) found in American building codes (ICC 2015). Note this is a broad range and many building products, such as plywood and OSB exterior sheathing and sheathing membranes may fall into this category, depending on the material, thickness, and local environment (e.g., RH).

This section will assess potential vapour movement inside these test walls based on measured vapour pressure differences, focusing primarily on potential vapour exchanges both with the exterior environment in the rainscreen cavity and with the indoor space at the drywall interface. To examine the general vapour pressure gradients and potential directions of vapour diffusion, using the calculation equations described in section 5.2.3.2, the (partial) vapour pressures are calculated based on the measured temperature and RH across each wall assembly at these points:

- in the indoor space,
- the exterior side of the poly vapour barrier or drywall (i.e., at measurement location 4),
- the interior surface of the OSB sheathing (i.e., at measurement location 2), and
- in the rainscreen cavity (i.e., at measurement location 1).

5.4.1 Vapour Pressure Profiles across Wall Assembly No. 1

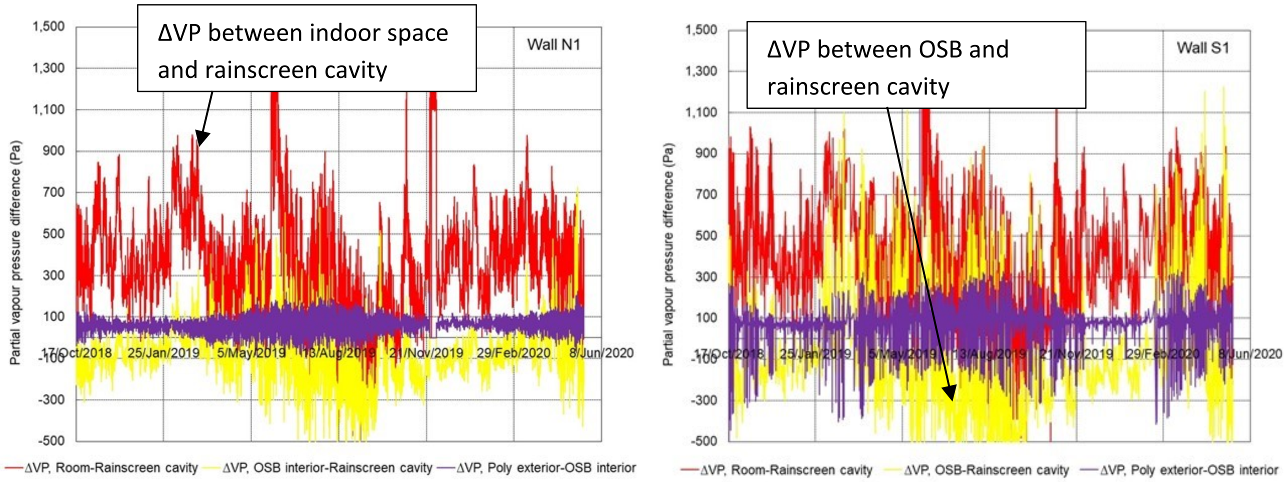
Wall assembly No. 1, a traditional deep-stud wall is used to illustrate the general vapour diffusion trends in this climate. Figure 42 shows the calculated vapour pressures across the north-facing wall panel N1 and the south-facing wall panel S1. The indoor vapour pressure (labelled as “Indoor VP” in the charts) clearly shows seasonal variations, fluctuating around 1200 Pa in the heating seasons and reaching 2000 Pa in late July and early August, when both of the indoor temperature and the RH exceed the target values. In the north-facing wall panel N1, the vapour pressures at the measurement locations across the wall assembly, including exterior to the poly vapour barrier (marked as “4 Poly exterior VP”), interior to the OSB sheathing (labelled as “2 OSB interior VP”), and the rainscreen cavity (labelled as “1 Rainscreen cavity VP”) are lower than the indoor vapour pressure, except for short periods in the summer. However, in the south-facing wall panel S1, the vapour pressures at those locations show much larger fluctuations due to the higher levels of solar irradiance in this orientation causing the vapour pressure inside the wall system to exceed the indoor vapour pressure much more frequently.



Locations for calculating partial vapour pressure: in rainscreen cavity (1 Rainscreen cavity VP); on interior surface of sheathing (2 OSB interior VP); exterior to poly vapour barrier (4 Poly exterior VP) and in the indoor space (Indoor VP)

Figure 42. Partial vapour pressure profiles of test wall panels N1 (left) and S1 (right)

The potential vapour diffusion directions are more clearly shown by the vapour pressure differences between two layers of components inside each test wall panel. For both wall panels N1 and S1 (i.e., the same wall assembly No. 1), potential outward vapour diffusion remains dominant from the indoor space towards the rainscreen cavity (indicated by the mostly positive "ΔVP, Room-Rainscreen cavity" in Figure 43) year-around, being typical of a heating-dominated climate. The poly vapour barrier thereby protects this wall from potential wetting caused by the warm and humid indoor environment. Inside the 2 by 8 wall cavities, there are mostly positive vapour pressure differences (i.e., "ΔVP, Poly exterior-OSB interior") between the poly vapour barrier (measured on its exterior surface) and the OSB sheathing (measured on its interior surface), indicating consistent potential outward vapour diffusion. Compared to the north orientation, there are much larger fluctuations in the vapour pressure differences, with the potential diffusion direction changing more frequently in the south-facing wall panel S1. But at the exterior boundary, i.e., between the OSB sheathing and the rainscreen cavity of S1, it appears the potential inward vapour diffusion (i.e., when "ΔVP, OSB interior-Rainscreen cavity" becomes negative) occurs almost as frequently as that towards the exterior (i.e., when "ΔVP, OSB interior-Rainscreen cavity" becomes positive) year-round. The potential inward vapour diffusion becomes more dominant in the winter, which must have resulted from the damper environment in the rainscreen cavity compared to the OSB sheathing but the similar temperatures between these two layers because of exterior insulation. This implies protecting the exterior sheathing and separating it from the rainscreen cavity environment should help improve the sheathing's durability performance. This will be further discussed below.



Locations for calculating partial vapour pressure differences (positive ΔVP = outward diffusion; negative ΔVP = inward diffusion):

- between indoor space and rainscreen cavity (ΔVP, Room-Rainscreen cavity)
- between poly (exterior surface) and OSB (interior surface) (ΔVP, Poly exterior-OSB interior), and
- between OSB sheathing (interior surface) and rainscreen cavity (ΔVP, OSB interior-Rainscreen cavity)

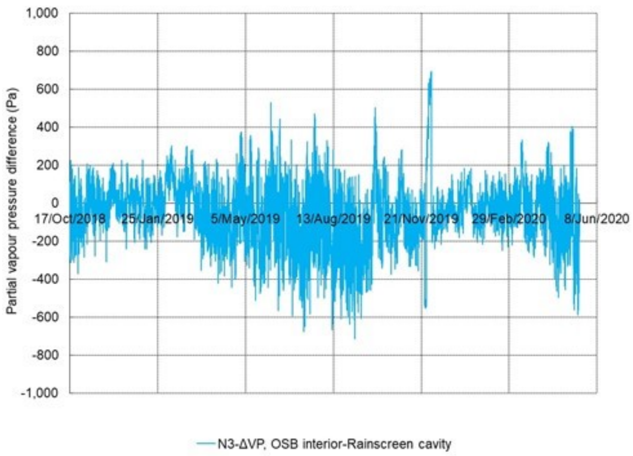
Figure 43. Partial vapour pressure difference profiles of test wall panels N1 (left) and S1 (right)

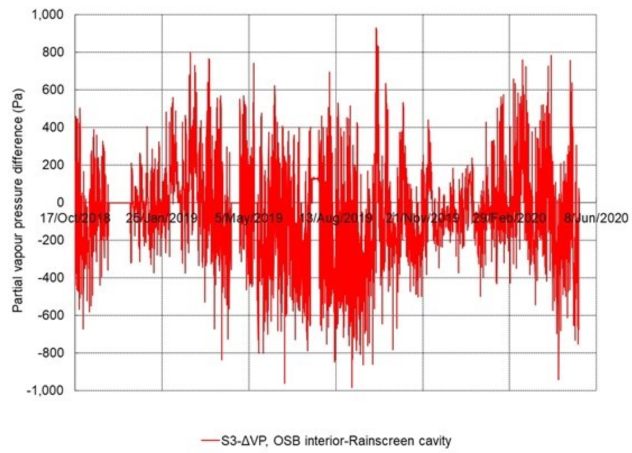
Most of this general analysis provided for wall No. 1 above also applies to other walls, since the indoor environment is the same for all these 12 test wall panels, and the environmental conditions in the rainscreen cavities remain similar for the test wall panels in the same orientation. The following discussions will therefore focus on vapour diffusion potential at the exterior and interior boundaries, respectively. Sections 5.4.2 and 5.4.3 assess the vapour pressure differences between the OSB sheathing and the rainscreen cavity to investigate potential vapour exchanges between the sheathing and the rainscreen cavity (i.e. that will cause drying towards the exterior or wetting due to inward vapour diffusion), and effect of exterior insulation. Section 5.4.4 focuses on potential moisture exchanges at the interior boundary (i.e., between the indoor space and the wall cavity), and the effects of the interior vapour control measure.

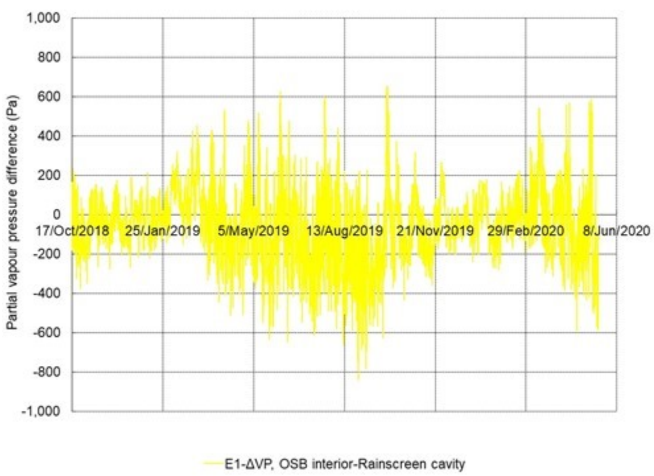
5.4.2 Vapour Diffusion through OSB Sheathing: Wall Assembly No. 3 in Three Wall Orientations

Wall assembly No. 3 is used as an example here to show potential vapour diffusion through the OSB sheathing in three orientations. In each chart below, only one curve is provided to show the trends and differences more clearly. Figure 44 aims to demonstrate the effect of wall orientation (north-, south- or east-facing) on vapour diffusion through the OSB sheathing of wall assembly No. 3 by showing the vapour pressure differences between the interior surface of the OSB sheathing and the rainscreen cavity for each orientation. Note that between these two measurement points, sheathing membrane and rigid stone wool insulation are also present.

Although the absolute magnitude of the vapour pressure differences varies, the direction of the vapour diffusion is similar among these three orientations. The potential vapour diffusion year-round is in both inward and outward directions, reflecting the relatively breathable nature of the OSB sheathing, the membrane, and the exterior insulation. Among these three orientations, the pressure differences are the largest in the south and the smallest in the north orientation, with the east-facing between the south and the north orientations.







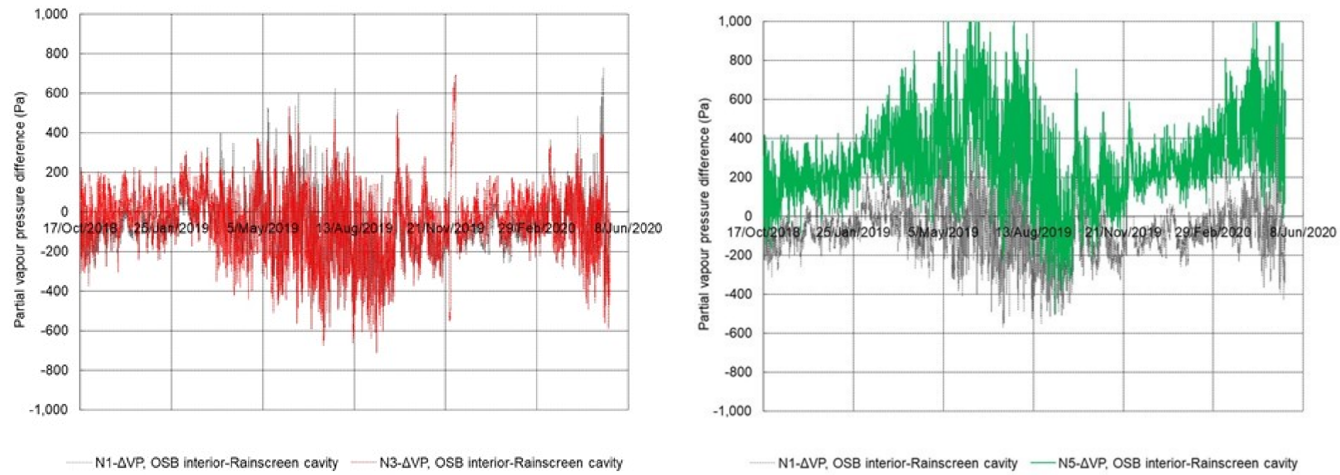
Calculated partial vapour pressure differences (positive ΔVP = outward diffusion; negative ΔVP = inward diffusion) between interior surface of OSB sheathing and rainscreen cavity (ΔVP, OSB interior-Rainscreen cavity) of wall assembly No. 3 with stone wood insulation, and E1 with no exterior insulation:

- north-facing test wall panel N3 (top, left)
- south-facing wall panel S3 (top, right)
- east-facing wall panel E1 (bottom)

Figure 44. Partial vapour pressure differences for three orientations of wall assembly No. 3 with stone wool exterior insulation

5.4.3 Vapour Diffusion through OSB Sheathing: Effect of Exterior Insulation

The effect of exterior insulation on the potential vapour flow through the OSB sheathing depends on the insulation type (primarily its vapour permeance). When the exterior insulation is highly vapour permeable, such as the stone wool insulation used in wall No. 3, its effect is small and the vapour exchanges at the OSB sheathing should therefore be close to those in wall No. 1, which does not have exterior insulation (Figure 45, left). Wall No. 3 therefore achieves a higher level of thermal insulation compared to wall No. 1 yet retains the vapour flow characteristics of wall No. 1. Apparently, exterior insulation with low vapour permeance, such as the foil faced-polyiso used in wall panel N5, has a much larger effect and significantly increases the vapour pressure differences between the OSB sheathing and the rainscreen cavity, relative to the same reference wall panel N1 (Figure 45, right). In wall panel N5, the potential outward vapour flow remains dominant, except for a short period of time in the summer (July, August). This indicates there is a need of wall N5 for outward drying, which is, however, hindered by the low vapour permeance of the exterior insulation. On the other hand, low-permeance exterior insulation can prevent inward vapour drive when the rainscreen cavity is warm and humid, typically in warm weather and especially after rain events, which do not occur often in Vancouver. Overall, for wall assembly No. 5, its performance appears to be limited by the low vapour permeance of the exterior insulation.

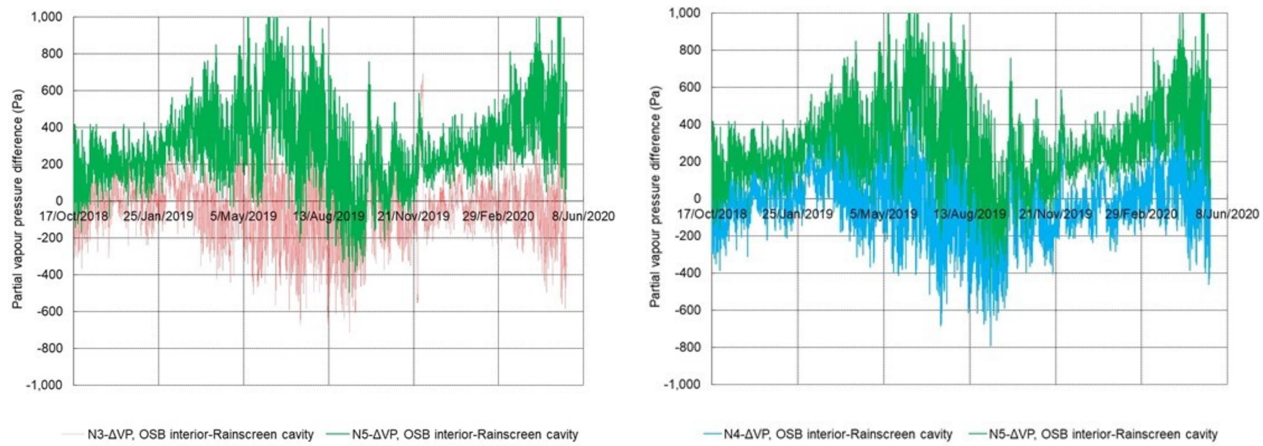


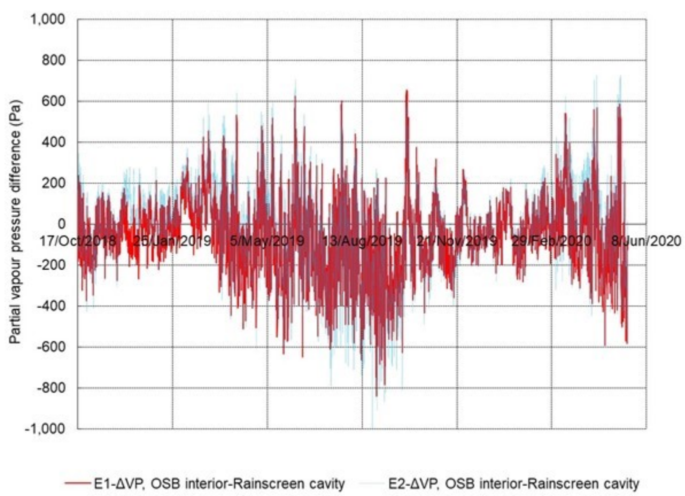
Comparison of calculated partial vapour pressure differences (positive ΔVP = outward diffusion; negative ΔVP = inward diffusion) between OSB sheathing (interior surface) and rainscreen cavity (ΔVP, OSB interior-Rainscreen cavity) for 3 wall panels:

- Left - N1 (no exterior insulation) vs N3 (exterior 1.5 in. stone wood insulation)
- Right - N1 (no exterior insulation) vs N5 (exterior 1 in. thick faced-polyiso board)

Figure 45. Comparison between wall panels N1, N3 (stone wool exterior insulation), and N5 (foil faced-polyiso)

In summary, the vapour pressure differences between the OSB sheathing and the rainscreen cavity is a good indicator of the vapour permeance of the exterior insulation (Figure 46). For example, it appears the 1 in. XPS used in wall panel N4 is less permeable than the stone wool insulation in wall panel N3 but certainly more permeable than the 1 in. thick faced-polyiso board, and the EPS used in the east-facing test wall panel E2 is similar to the stone wool insulation in E1, in terms of vapour permeance. The permeance of the exterior insulation affects the wetting and drying behaviour of the OSB sheathing and possibly the entire wall assembly, whether that be due to the moisture from the seasonal variations in RH and temperature, or unanticipated water ingress.





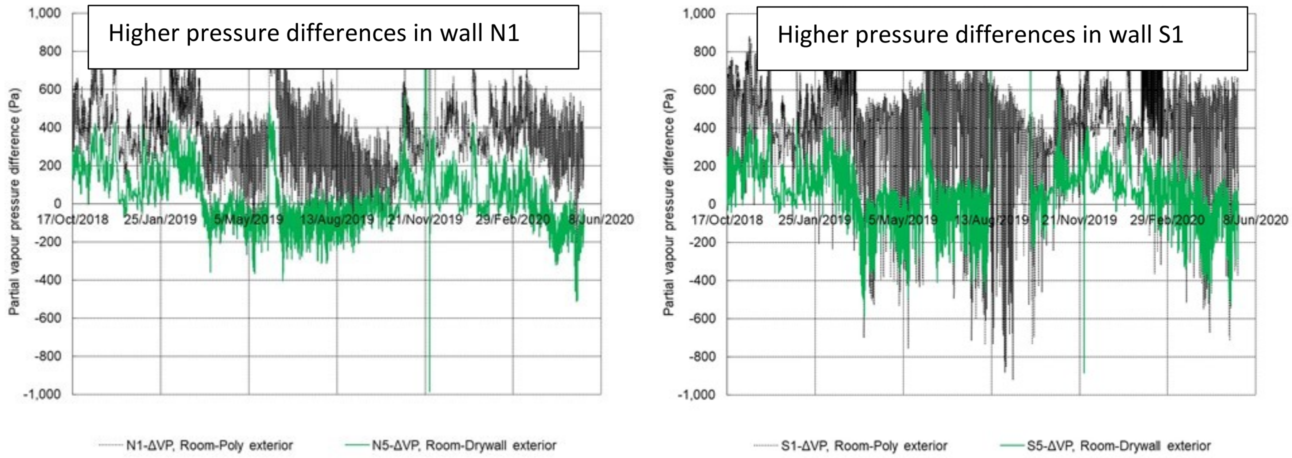
Comparison of calculated partial vapour pressure differences (positive ΔVP = outward diffusion; negative ΔVP = inward diffusion) between interior surface of OSB sheathing and rainscreen cavity (ΔVP, OSB interior-Rainscreen cavity):

- N3 (stone wool) and N5 (polyiso) (top, left)
- N4 (XPS) and N5 (polyiso) (top, right)
- E1 (stone wool) and E2 (EPS) (bottom)

Figure 46. Comparison of partial vapour pressure differences between wall panels with and without exterior insulation

5.4.4 Vapour Diffusion through Drywall: Effect of Interior Vapour Control

Wall assembly No. 1 with an interior poly vapour barrier, and wall assembly No. 5 with an interior vapour-retarding paint on its drywall are compared to assess the effect of interior vapour control methods on potential vapour diffusion through drywall and the moisture exchanges with the indoor environment. Figure 47 shows the vapour pressure differences between the indoor space and the exterior side of the poly vapour barrier (N1-ΔVP, Room-Poly exterior) in wall assembly No. 1, and those between the indoor space and exterior side of the drywall (N1-ΔVP, Room-Drywall exterior) in wall assembly No. 5. In both north and south orientations, the pressure differences in wall assembly No. 1 remain much higher, implying the poly vapour barrier in wall assembly No. 1 effectively resists the higher indoor vapour pressure and thereby reduces wetting caused by the indoor humidity.



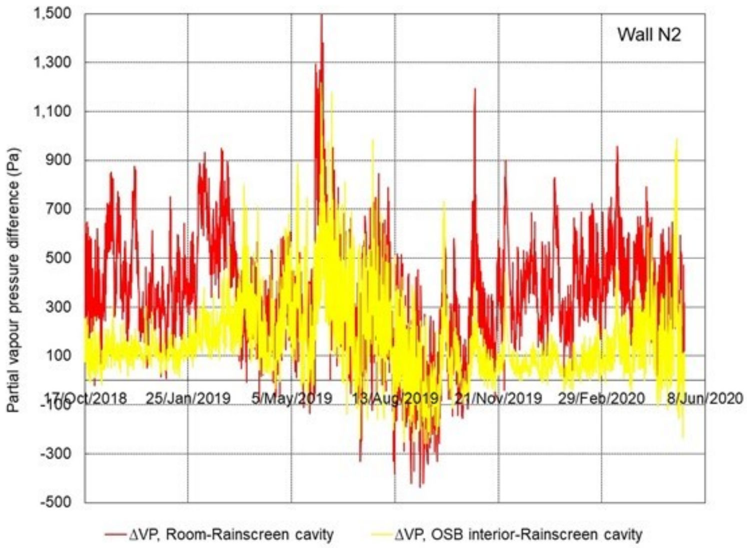
Comparison of calculated partial vapour pressure differences (positive ΔVP = outward diffusion; negative ΔVP = inward diffusion) between the indoor space and the exterior side of the poly vapour barrier (N1-ΔVP, Room-Poly exterior) in wall assembly No. 1, and the indoor space and the drywall (N1-ΔVP, Room-Drywall exterior) in wall assembly No. 5

- north-facing wall panels N1 and N5 (left)
- south-facing wall panels S1 and S5 (right)

Figure 47. Comparison of partial vapour pressure differences between indoor space and poly vapour barrier of wall assembly No. 1 and those between indoor space and drywall of assembly No. 5

5.4.5 Vapour Diffusion across Wall Panel N2

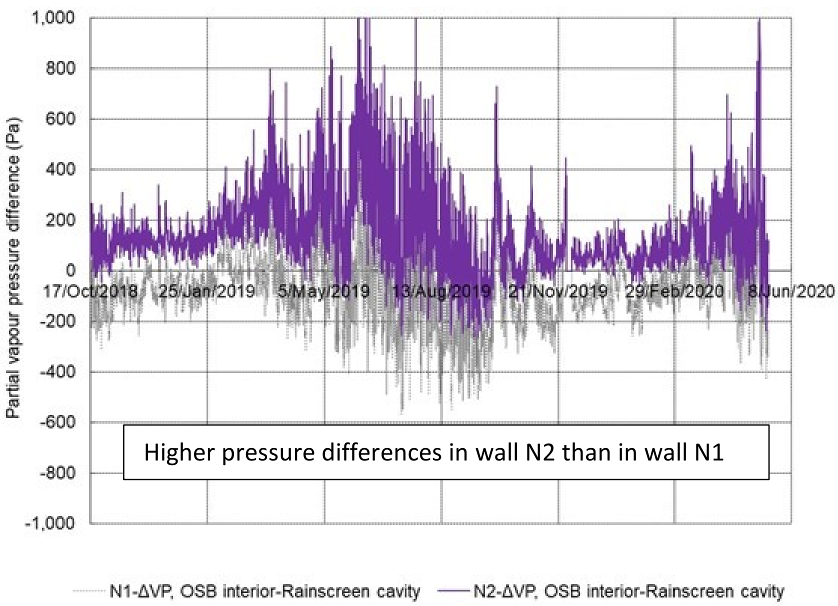
Wall No. 2 represents a more recently developed deep-cavity (double studs) wall with ocSPF and an interior vapour-retarding paint. Examining the north-facing test wall panel N2 (Figure 48), the potential outward vapour diffusion overall remains dominant from the indoor space to the rainscreen cavity, with the vapour pressure differences between the indoor space and the rainscreen cavity (ΔVP, Indoor space-Rainscreen cavity) being mostly positive on a yearly basis. This suggests the vapour-retarding paint may not be performing as expected and that a stronger interior vapour control method to reduce outward moisture movement may be needed. The vapour pressure differences between the interior surface of the OSB sheathing and the rainscreen cavity also mostly remain positive, indicating possibly damper conditions at the sheathing than in the rainscreen cavity, since the temperature between these two layers should be similar, without exterior insulation to keep the sheathing much warmer. Compared to test wall panel N1, the vapour pressure at the OSB sheathing of wall panel N2 is much higher than that in wall panel N1 (Figure 49), indicating damper sheathing in wall panel N2, given a lack of exterior insulation in both walls. Note the chance for the sheathing's temperature to fall below the dew point is also very high for both wall panels N1 and N2 (section 5.2.3.2).



Comparison of calculated partial vapour pressure differences (positive ΔVP = outward diffusion; negative ΔVP = inward diffusion) between the following in test wall panel N2:

- indoor space and rainscreen cavity (ΔVP, Room-Rainscreen cavity), and
- interior side of OSB sheathing and rainscreen cavity (ΔVP, OSB interior-Rainscreen cavity)

Figure 48. Partial vapour pressure differences in test wall panels N2



Comparison of calculated partial vapour pressure differences (positive ΔVP = outward diffusion; negative ΔVP = inward diffusion) between the following in test wall panels N1 and N2:

- interior side of OSB sheathing and rainscreen cavity (ΔVP, OSB interior-Rainscreen cavity)

Figure 49. Comparison of partial vapour pressure differences between OSB sheathing and rainscreen cavity in test wall panels N1 (with fiberglass batt insulation) and N2 (with ocSPF)

5.5 Prediction of Mould Growth Potential and Comparison with Field Observation

5.5.1 Prediction of Mould Growth Potential based on Mould Index

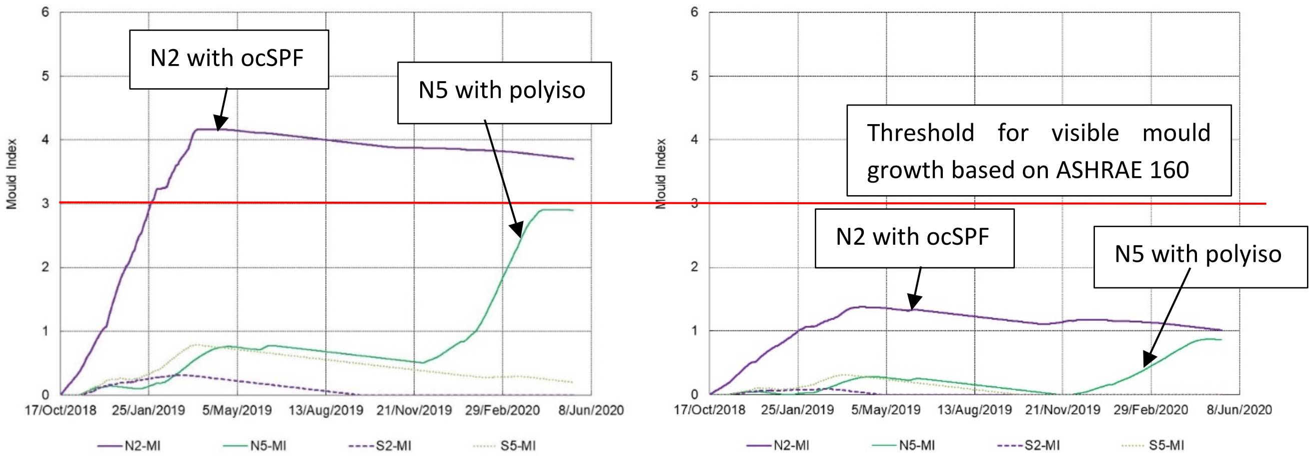
5.5.1.1 Calculation of Mould Index

A mould index (MI) is calculated to predict mould growth potential of the OSB sheathing of these test wall panels based on the standard ASHRAE 160 (2016). The standard classifies building materials into four sensitivity classes: Very Sensitive (e.g., untreated wood, including lots of nutrients for biological growth), Sensitive (e.g., planed wood, paper coated products, wood-based boards), Medium Resistant (e.g., cement or plastic based materials), and Resistant (e.g., glass or metal products) as different levels of susceptibility to mould growth, based on testing primarily conducted by VTT (i.e., the Technical Research Centre of Finland, Viitanen and Paajanen 1988). MI is calculated using the hourly temperature and RH measured at the surface of a given material and summed over time to provide an indication of whether the environment favours mould growth or not, since most fungi prefer a warm and damp environment. The MI result is designed to range from 0 (i.e., no mould growth) to 6.0 (i.e., with the surface fully covered with mould), and a rating of 3.0 indicates visible mould growth on the surface. As part of the more detailed calculations, the surface critical RH, i.e., the threshold RH for mould growth, is calculated as a function of surface temperature for a given sensitivity class. For example, for both Very Sensitive and Sensitive classes, which are typically assumed for wood products based on the standard, the surface critical RH is 80% when the surface temperature is above 20°C; it goes up to 100% when the temperature is between 0°C and 20°C. On the other hand, a decline in mould growth will occur if the current hour has a surface temperature below 0°C or a surface RH below the critical RH.

5.5.1.2 Mould Index of Test Walls

The MI values provided in Figure 50 are based on the hourly temperature and RH measured from the interior surface of the OSB sheathing at its mid-height (i.e., T2, RH2) during the 19-month test. The OSB sheathing is assumed to be either “Very Sensitive” or “Sensitive”. The calculations suggest that only two wall assemblies No. 2 (i.e., wall panels N2, S2) and No. 5 (i.e., wall panels N5, S5) show MI over 0, indicating the service environments inside these four wall panels are favourable for mould growth at least for some time during the test. For the “Very Sensitive” class, the MI value of test wall panel S2 reaches 0.3 over the first winter but drops to zero when the first summer is over; there is no increase in the MI over the second winter. The MI of wall panel S5 reaches a maximum of about 0.8 by mid-March after the first winter, and afterwards gradually decreases until the second spring when the test was terminated. Only test wall panel N2 shows an accumulated MI exceeding 3.0 during the 19-months test. Its MI value increases almost linearly after the test starts and exceeds 4.0 by mid-March after the first winter. It then drops slowly when the weather becomes warmer and drier; this decreasing trend continues into the second winter when it reaches an MI of 3.7 by the second spring. For test wall panel N2, the decrease in MI over the second winter, in contrast to the increase in the first winter is likely attributable to the increased vapour resistance of the wall’s interior face when its drywall was repainted in November 2019. In terms of test wall panel N5, its MI reaches 0.7 after the first winter season. It reduces slightly over the summer and then increases rapidly over the second winter, exceeding 2.9 by April 2020. Afterwards, it remains level until the completion of the testing in May 2020. It is likely that the MI of wall panel N5 would continue to increase and exceed 3.0 if the test were not terminated. For comparison, assuming the “Sensitive” class for OSB leads to much lower MI value. In this class, the highest MI of wall panel N2 is below 1.5, indicating no visible mould growth during the entire test period.

To conclude, the MI calculations suggest test wall panels N2 and N5, particularly N2 may show mould growth resulting from vapour diffusion. Water introduced through intentional injection certainly increases the likelihood of mould growth; however, the MI is not calculated since the impact of water injection on surface RH measurements may not be consistent among these test wall panels. MI may also be applied to assess the mould growth potential in the rainscreen cavity; but it is not a priority in this study.[14]



Comparison of MI (ASHRAE 2016) computed using the hourly temperature and RH readings for wall assemblies No. 2 and No. 5 at the interior surface of the OSB sheathing at the panel mid-height (i.e. T2, RH2), assuming OSB's sensitivity to mould growth is:

- "Very Sensitive" (left chart)
- "Sensitive" (right chart)

Figure 50. Calculated Mould Index (MI) using two mould sensitivity classes and temperature/relative humidity measurements on the OSB sheathing of wall assemblies No. 2 and No. 5 (wall panels N2, S2, N5, and S5)

5.5.2 Field Observation of Mould Growth

The wood components, particularly the OSB sheathing were carefully checked when the test wall panels were deconstructed in July-August 2020. The field inspection was focused on the OSB's interior surface for comparison with the MI calculations above, given the fact that the temperature and RH used for calculating MI were measured from the interior surface. It was found that all of the OSB sheathings, including that of the test wall panels N2 and N5 were clean, without any visible mould growth (Figure 51). In terms of wall assembly No. 2, the spray foam appeared to seal the entire OSB sheathing on its interior surface and may have prevented mould growth by reducing the oxygen supply, as suggested by other researchers (Smegal et al. 2017).

The field observations suggest that there is a discrepancy between the mould prediction based on the standard ASHRAE 160 and real mould growth potential of the OSB sheathing, when the OSB sheathing is assumed to be "Very Sensitive" to mould growth. There could be a few reasons for this. First, it is well known that the MI prediction was based on limited laboratory testing conducted in Europe using mostly European wood species and products. There are always differences in durability performance among materials and products from different

[14] In terms of the conditions in the rainscreen cavity, it is found that this semi-exterior environment may cause mould growth based on the same prediction using MI, if wood is exposed to, particularly in the damper north orientation (Figure 116). This indicates that the wood furring used in the rainscreen cavities would require preservative treatment or use of naturally durable wood to ensure long-term durability. Adjacent exterior sheathing, such as the OSB sheathing of the test wall panels, should also be protected against this environment. Protection is typically provided by using a sheathing membrane and/or exterior insulation, as the test walls in this study.

sources. Second, mould growth can be highly variable, given the large variations in both wood and fungi growth. Lowering the sensitivity class of the OSB sheathing to “Sensitive” considerably reduces the calculated MI and appears to better match the field observations.

Panel N2

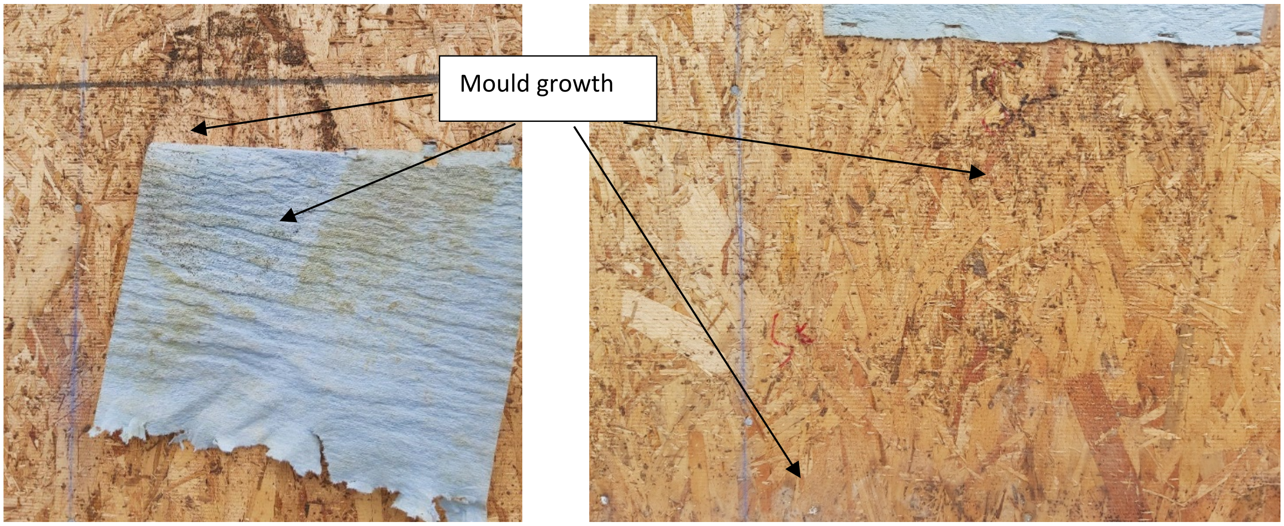
Panel N5

Panel S2

Panel S5

Figure 51. Photos of interior appearance of OSB sheathing of wall panel N2, N5, S2 and S5, following completion of testing in July 2020

On the exterior surface of the OSB sheathing, no mould indicative of outbound or inbound vapour diffusion was observed, either. However, mould was observed around and below the wetting pads of wall panels N5 and S5, with more severe mould growth on wall panel N5 (Figure 52). As no mould was found around the wetting pads of the other wall panels, this again proves that the foil-faced polyiso exterior insulation used in this wall does not allow drying to occur.



Panel N5 with foil-polyiso exterior insulation

Panel S5 with foil-polyiso exterior insulation

Figure 52. Photos of exterior appearance of OSB sheathing of wall panel N5 and S5, following completion of testing in July 2020

6 CONCLUSIONS

This report provides hygrothermal performance data for six types of R22 exterior wood-frame wall assemblies, with 12 test wall panels in a test hut in FPInnovations' Vancouver laboratory. The following conclusions are drawn based on a large amount of data collected over a 19-month period, covering two winters and one summer season from October 2018 to May 2019. Except occasionally during the summer months[15], the indoor environment of the test hut was maintained around 21°C and 50% RH. Aside from comparing the walls subjected to vapour diffusion, water was injected onto the exterior surface of each OSB sheathing over three different seasonal conditions (summer, early winter, and late winter) to quantify the drying capacity and the resiliency of each wall against potential incidental water leaks that could occur in building service. The impact of air leakage into the wall assemblies was not tested as part of this experimental setup.

The following are general observations and conclusions:

- The test method has proved to be efficient for assessing the hygrothermal performance of exterior wall assemblies, providing meaningful data for assessing the relative performance of different wall assemblies.
- The measured temperature and RH from the test walls' ventilated rainscreen cavities, which are defined in this report as a simplified exterior boundary for comparing wall performance, well reflect the coastal climate of Vancouver, with the winter being mild and damp and the summer being warm and much drier.
- Among the three orientations (north, south, and east) covered in this test, the south-facing walls are warmer and drier than the north-facing counterparts, with the east between the north and the south, due to different solar effects.

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[15] The test hut was not air conditioned.

- Consistent results are obtained from measuring the service environmental conditions, the moisture content of OSB sheathing, and using the measurements to assess potential vapour diffusion in these test walls.
- Related to wall design, the split-insulated walls have warmer OSB sheathing and are much less likely for the sheathing temperature to fall below the dew point of the indoor air, compared to the walls without exterior insulation. When exterior insulation is used, there are negligible differences in the sheathing temperatures among the different insulation types, i.e., the type has little impact on the capacity to keep the sheathing warm when the rated R-values are approximately the same. However, the vapour permeance of the exterior insulation affects the wall's drying performance; vapour-permeable exterior insulation allows drying towards the exterior.
- The interior vapour control of the building envelope remains important for Vancouver's mild climate in humid residential buildings (e.g., with RH of around 50% during wintertime). The poly vapour barrier used in walls No. 1, No. 3, and No. 4 appears to be effective in minimizing outward vapour diffusion and the related wetting. For wall assemblies No. 2 or No. 5, the use of an interior vapour-retarding paint coupled with the wall's drying capacity does not sufficiently protect each wall from wetting caused by outward migration of indoor humidity for the indoor conditions, wall configurations and materials tested here. Further research is to be carried out on this.
- None of the test wall panels' OSB sheathing shows visible mould growth resulting from outbound vapour diffusion, although the mould prediction based on the MI following the standard ASHRAE 160 and assuming the OSB sheathing falls into the "Very Sensitive" class suggests that north-facing test wall panels N2 and N5 should have shown mould growth by the end of the test. Wall assembly No. 5 with exterior foil faced-polyiso insulation including both wall panels N5 and S5 (south-facing) shows mould growth on the exterior surface of its OSB sheathing in and around the wetting pad, suggesting poor drying after water injection.

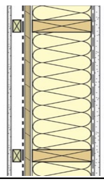
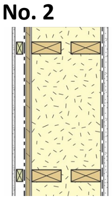
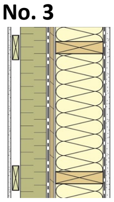
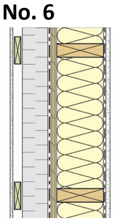
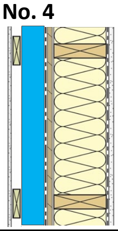
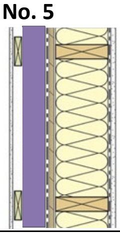
Given the importance of ensuring that there is adequate vapour diffusion, more detailed results of the study are summarized below starting with the two deep-stud wall assemblies No. 1 and No. 2, followed by the four split-insulated wall assemblies (from No. 3, No. 4, No. 5 to No. 6,) in order of increasingly reduced vapour permeance of the exterior insulation used. The performance is primarily based on the data collected from the north-facing test wall panels N1-N5 for the wall assemblies from No. 1 to No. 5 and the east-facing test wall panel E2 for wall assembly No. 6, since south-facing walls are drier than north-facing or east-facing counterparts. The table below provides a concise summary and comparison for these six wall assemblies.

- For the deep-stud wall assembly No. 1, which is built with nominal 2 in. by 8 in. wood framing with an interior poly vapour barrier, the measured RH from the interior surface of its OSB sheathing remains below 80% over both winter seasons during the test; the measured MC at its mid-depth stays below 16% even after water injection. This wall can dry towards the exterior quickly. The test shows this wall should not have a large durability concern in the Vancouver climate, provided it is constructed airtight.
- For the deep-stud (double 2 in. by 4 in. studs) wall assembly No. 2, with ocSPF together with a vapour-retarding paint initially applied on the interior surface of the foam, and another coating of vapour-retarding paint applied on its drywall before the start of the second winter, the measured RH from the interior surface of its OSB sheathing stays above 90% over the first winter and decreases to below 90% but still well above 80% over the second winter. The test results indicate this wall's OSB sheathing is susceptible to mould growth, which is confirmed with the ASHRAE 160 standard MI value which exceeds

3.0 during the test period, when it is assumed the OSB sheathing falls into the “Very Sensitive” class. The MC measurements from its OSB sheathing indicates moisture accumulation during the winter. However, the wall shows good drying capacity, with drying towards both interior and exterior possible when conditions permit. Use of spray foam typically improves airtightness, which can reduce vapour condensation potential caused by air leakage. Further research including material characterization and hygrothermal modelling is planned for this wall to improve specifications.

- For wall assembly No. 3 with 1.5 in. rigid stone wool exterior insulation (vapour permeance of about 1200 ng/(Pa·s·m^2) (about 21 US perm)), together with an interior poly vapour barrier, the measured RH from the interior surface of its OSB sheathing consistently remains below 80% over the entire test period. Among the six wall types tested, this wall should protect the OSB with the lowest humidity level in service. The MC measured from the OSB sheathing consistently stays below 16%, even after water injection. Therefore, this wall is able to manage vapour diffusion from the interior space or incidental water leaks from the exterior.
- For wall assembly No. 4 with 1 in. XPS exterior insulation (vapour permeance of 87 ng/(Pa·s·m^2) (about 1.5 US perm)), together with an interior poly vapour barrier, the measured RH from the interior surface of its OSB sheathing remains below 80% over the entire test period. The MC measurements from the OSB sheathing slightly exceeds 16% after each phase of water injection. This wall shows limited vapour diffusion drying capacity due to the lower vapour permeance of the XPS compared to EPS or stone wool, with drying rates lower than those of wall No. 3 or No. 6 noted below.
- For wall assembly No. 5, with 1 in. thick foil faced-polyiso exterior insulation (vapour permeance close to 0), together with an interior vapour-retarding paint on its drywall, the RH measurements from the interior surface of its OSB sheathing consistently stays above 80%, suggesting high mould growth potential over the two winter seasons. This is also confirmed with the relatively high MI when the sheathing is assigned with the “Very Sensitive” mould growth classification. However, no mould is found on the interior or the exterior surface of the sheathing if the sheathing is subject only to vapour diffusion. But mould is found around and below the wetting pads. Compared to the other walls tested, this wall has lower tolerance, when water penetrates between the impermeable exterior insulation and the wood frame, due to its minimal capacity to dry towards the exterior. Note that this assembly exceeds the current building code (e.g., National Building Code of Canada, BC Building Code) section 9.25 outboard to inboard insulation ratio requirements for the tested climate zone.
- For wall assembly No. 6 with 1.5 in. EPS exterior insulation (vapour permeance of about 130 ng/(Pa·s·m^2) (about 2 US perm)), together with an interior poly vapour barrier, the measured RH from the interior surface of its OSB sheathing consistently remains below 80% over the entire test period. The MC measured from the OSB sheathing consistently stays below 16%, even after water injection. Therefore, this wall is able to manage vapour diffusion from the interior space or incidental rain leaks from the exterior.

Table 3. Summary of hygrothermal performance of six wall assemblies in Vancouver's climate based on this test

Wall assembly	Wall features	RH level on OSB's interior surface in winter	Moisture accumulation risk on OSB due to outward vapour diffusion from humid indoor space	Drying capacity after incidental water leaks behind sheathing membrane	Overall long-term durability performance indication
No. 1 	Deep wall studs with interior poly	Below 80%	Low risk	Reasonably good drying (Drying can occur towards the exterior.)	Acceptable when it is built to be airtight
No. 2 	Double wall studs with ocSPF, together with an interior vapour-retarding paint (on foam/drywall)	Exceeding 90% with the initial vapour-retarding paint on the foam; above 80% with another interior vapour-retarding paint on drywall	Considerable moisture accumulation risk due to high indoor humid in wintertime	Reasonably good drying (Drying can occur towards both interior and exterior.)	There is mould growth potential. The wall is not suitable for buildings with a high indoor moisture load, unless a more impermeable interior vapour control is applied.
No. 3 	Highly permeable exterior insulation (1.5 in. stone wool, with a vapour permeance of 1200 ng/(Pa·s·m^2) (about 21 US perm)), together with interior poly	Below 80%	Low risk	Good drying (Drying can occur quickly towards the exterior.)	Good
No. 6 	Permeable exterior insulation (1.5 in. EPS, with a vapour permeance of about 130 ng/(Pa·s·m^2) (about 2 US perm)), together with interior poly	Below 80%	Low risk	Good drying (Drying can occur fast enough towards the exterior.)	Good
No. 4 	Lower permeance exterior insulation (1 in. XPS, with a vapour permeance of 87 ng/(Pa·s·m^2) (about 1.5 US perm)), together with interior poly	Below 80%	Low risk	Acceptable drying performance (Slow drying can occur towards the exterior through the exterior insulation.)	Acceptable
No. 5 	Impermeable exterior insulation (1 in. foil-faced polyiso, with vapour permeance close to 0), together with an interior vapour-retarding paint	Persistently above 80%	Considerable moisture accumulation risk due to high indoor humidity in wintertime	Poor drying (Very limited drying can occur only towards the interior when conditions permit.)	There is durability risk from outward vapour diffusion when there is a high indoor moisture load or incidental water leaks.

7 NEXT STEPS

- Validate hygrothermal modeling with field measurement results
- Provide recommendations to improve the design and construction of energy efficient wood-frame buildings in collaboration with RDH Building Science and BC Housing
- Disseminate information in the building science community

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APPENDIX I: MATERIAL PROPERTIES

Table 4. Key properties of the materials used to build the test walls based on literature* and limited laboratory testing

Material	Thickness mm (in.)	Density from literature kg/m³(lbs/ft³)	Density based on testing kg/m³(lbs/ft³)	Thermal resistance		Vapour permeance based on literature dry cup (wet cup)	
				RSI-value (m²·K)/W	R-value ft²·°F·hr/Btu	ng/Pa•s•m²	US Perm
Stone wool rigid board	38 (1.5)	128 (8)		0.7	4	1768	30.8
Extruded polystyrene	25 (1)	40 (2.5)	40 (2.5)	0.88	5	87	1.5
Faced-polyiso board	25 (1)	40 (2.5)	40 (2.5)	1.09	6.2	lower than 2.6	0.045
Expanded polystyrene, type 2	38 (1.5)	22 (1.4)		0.7	4	200	3.5
Open-cell spray foam	184 (7.2)	8.5 (0.53)		0.65	3.7	1218	21
OSB sheathing	11 (7/16)	680 (42.5) (Glass 2015)	628 (39.3)	0.11	0.62	110 (80) 112 (Kumaran et al. 2002)	1.9 (1.4) 2.0
Polyethylene sheet (6 mil)	0.15 (0.006)	-		-	-	3	0.05
Sheathing membrane, loose plastic sheet	0.2 (0.008)	-		-	-	1740 (based on wet cup)	30
Self-adhesive membrane	0.6 (0.02)					178 (157)	3.1 (2.8)
Drywall, no finish	12.7 (0.5)	500 (31.2) (Glass et al. 2015)	530 (33.1)			2800 (2600) (Glass et al. 2015)	49 (45) (Glass et al. 2015)
Drywall with latex primer and paint	12.7 (0.5)	700 (43.8)	530 (33.1)	0.08	0.45	580 (Glass 2013)	10
Drywall with latex primer and paint (Glass et al. 2015)	12.4 (0.489)	500 (43.8)				2000 (2000)	35 (35)
Drywall with latex primer and water-resistant paint			530 (33.1)				

*The properties provided for the insulation materials were extracted from manufacturers' information and based on 25 mm thick material.

APPENDIX II: WATER INJECTION SCHEDULE AND AMOUNTS

Table 5. Water injection schedule and amounts for each test wall

Phase A: July 22-26, 2019					
Date	Time	Water injection amount (mL)	Time	Water injection amount (mL)	Daily amount
22-Jul	10:30	20	3:30	20	40
23-Jul	10:30	20	3:30	20	40
24-Jul	10:30	20	3:30	20	40
25-Jul	10:30	20	3:30	20	40
26-Jul	10:30	20	3:30	20	40
Phase A total injected water amount					**200**
Phase B: Nov 12-22, 2019					
Date	**Time**	**Water injection amount (mL)**	**Time**	**Water injection amount (mL)**	**Daily amount**
12-Nov	10:30	20	3:30	20	40
13-Nov	10:30	20			20
14-Nov	10:30	20	3:30	5	25
15-Nov	10:30	20	3:30	5	25
18-Nov	10:30	20	3:30	5	25
19-Nov	10:30	20			20
20-Nov	10:30	20			20
21-Nov	10:30	20			20
22-Nov			2:00	20	20
Phase B total injected water amount					**215**
Phase C: Jan 20-31, 2020					
Date	**Time**	**Water injection amount (mL)**	**Time**	**Water injection amount (mL)**	**Daily amount**
20-Jan	10:30	20			20
21-Jan	10:30	20			20
22-Jan	10:30	20			20
23-Jan	10:30	20			20
24-Jan	10:30	20			20
27-Jan	10:30	20			20
28-Jan	10:30	20			20
29-Jan	10:30	20			20
30-Jan	10:30	20			20
31-Jan	10:30	20			20
Phase C total injected water amount					**200**

APPENDIX III: TEST RESULTS: WALL ASSEMBLY NO. 1

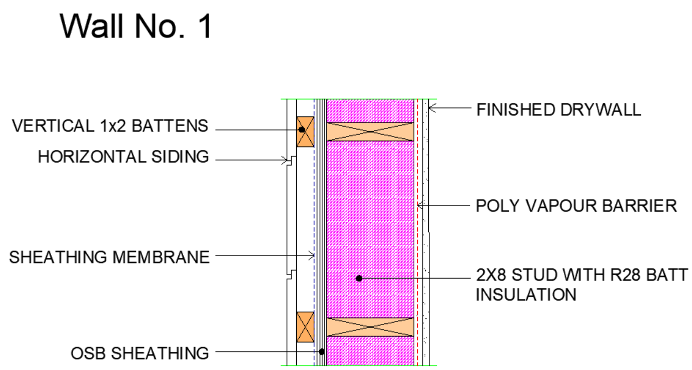


Figure 53. The wall assembly of wall assembly No. 1

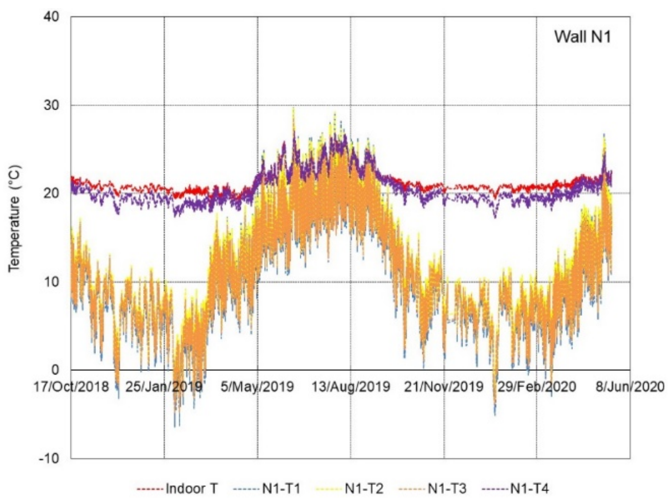


Figure 54. Temperature profiles across north-facing wall panel N1

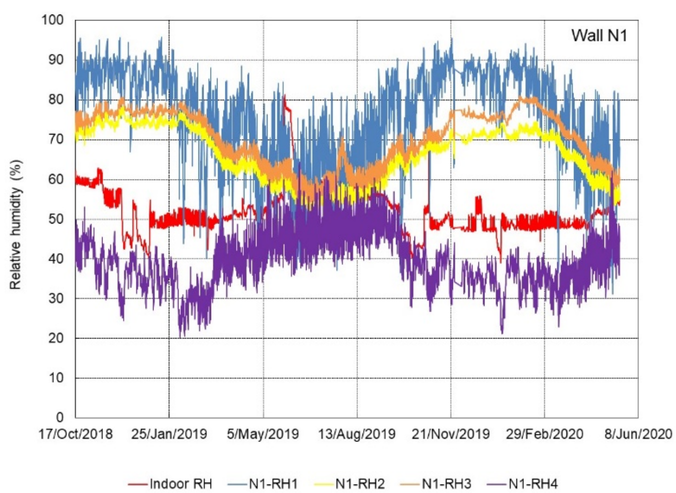


Figure 55. Relative humidity profiles across north-facing wall panel N1

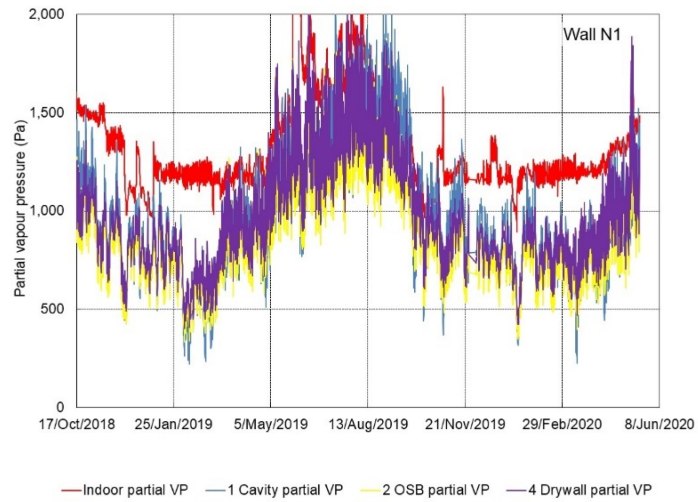


Figure 56. Partial vapour pressures across north-facing wall panel N1

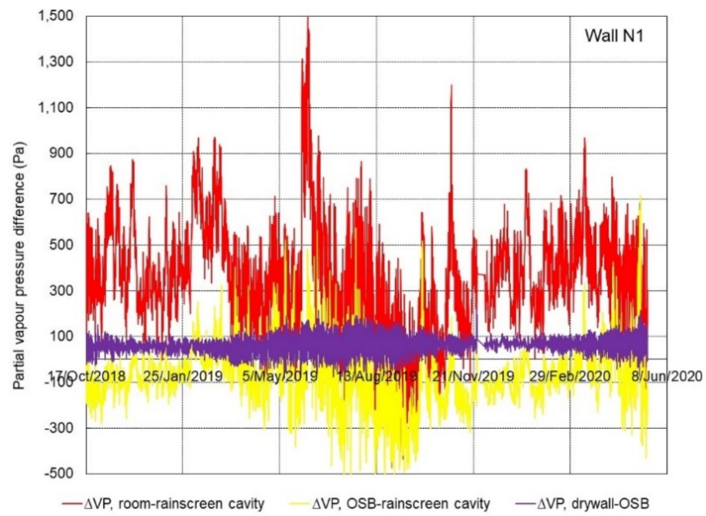


Figure 57. Partial vapour pressure differences across north-facing wall panel N1

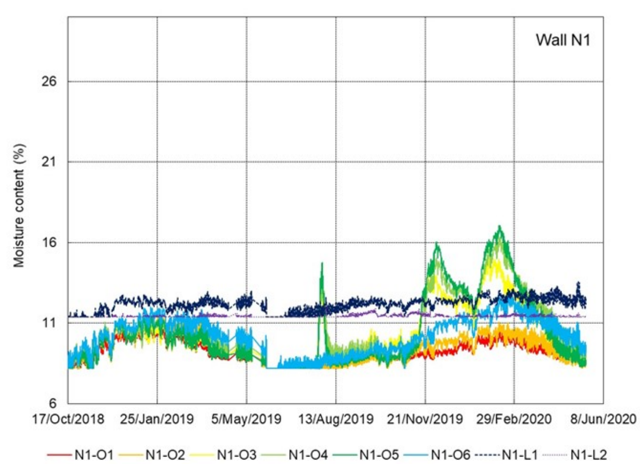


Figure 58. Wood moisture content measurements from north-facing wall panel N1

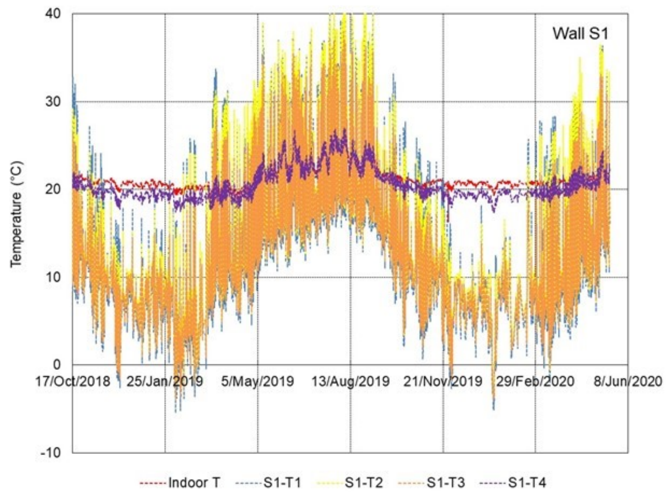


Figure 59. **Temperature profiles measured from south-facing wall panel S1**

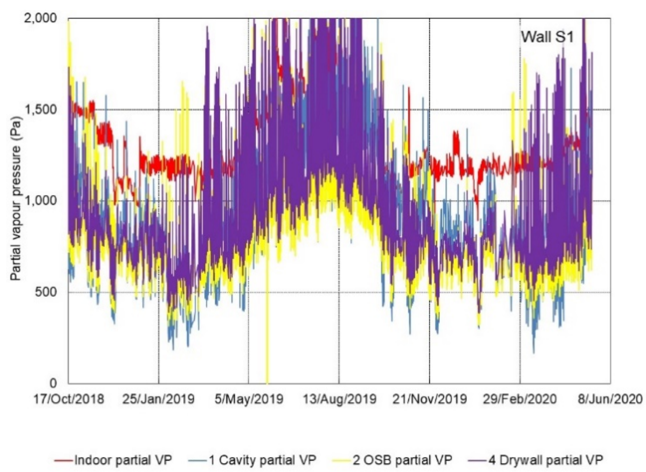


Figure 60. **Relative humidity profiles across south-facing wall panel S1**

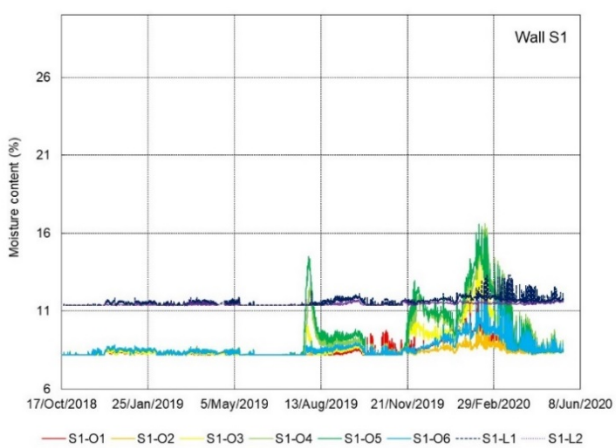


Figure 61. **Wood moisture content measurements from south-facing wall panel S1**

APPENDIX IV: TEST RESULTS: WALL ASSEMBLY NO. 2

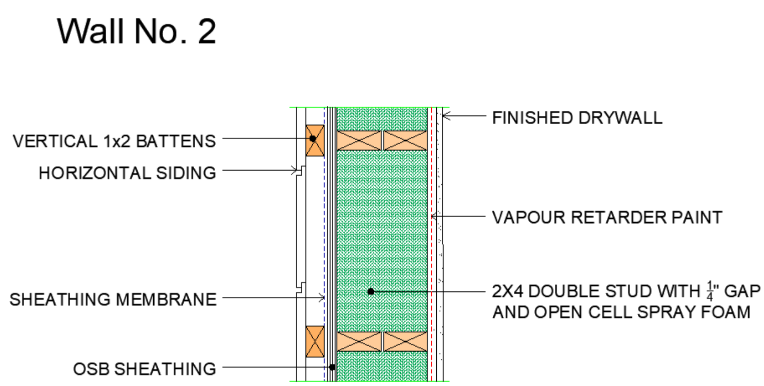


Figure 62. **The wall assembly of wall assembly No. 2**

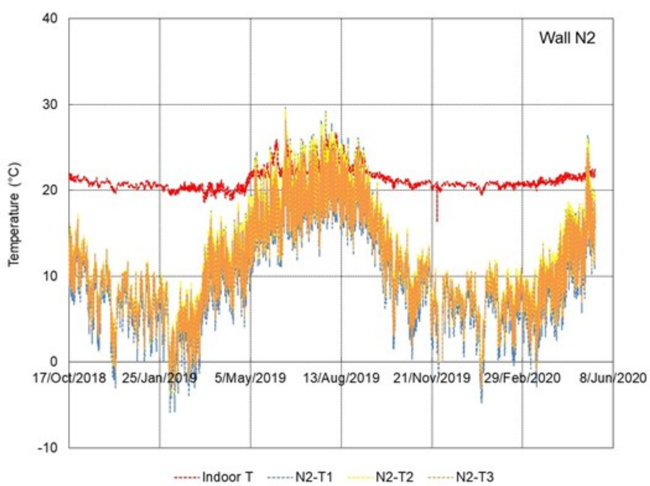


Figure 63. **Temperature profiles measured from north-facing wall panel N2**

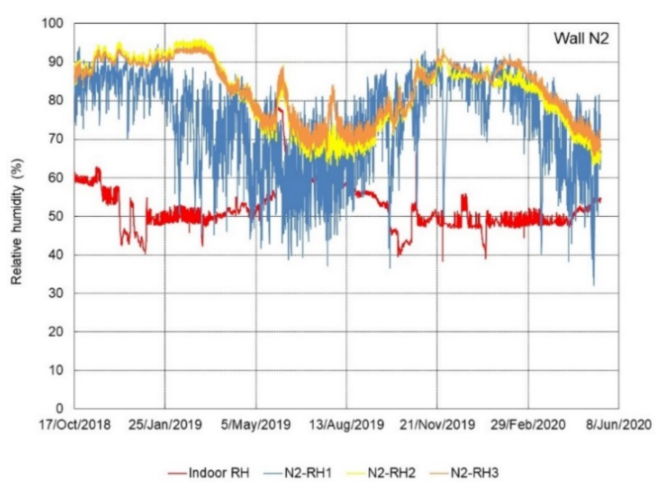


Figure 64. **Relative humidity profiles across north-facing wall panel N2**

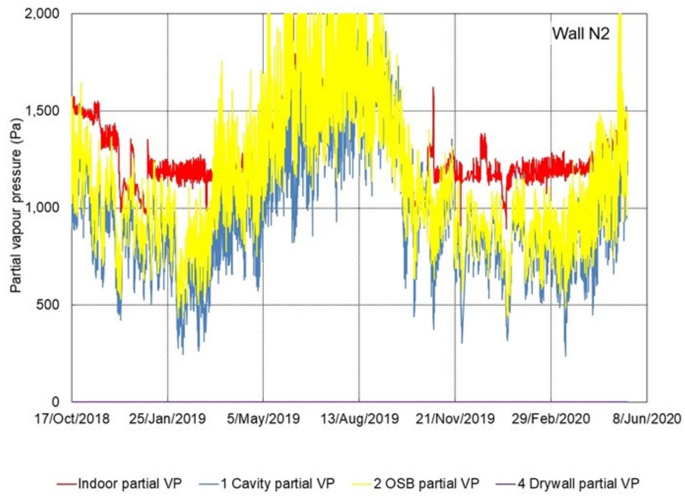


Figure 65. **Partial vapour pressures across north-facing wall panel N2**

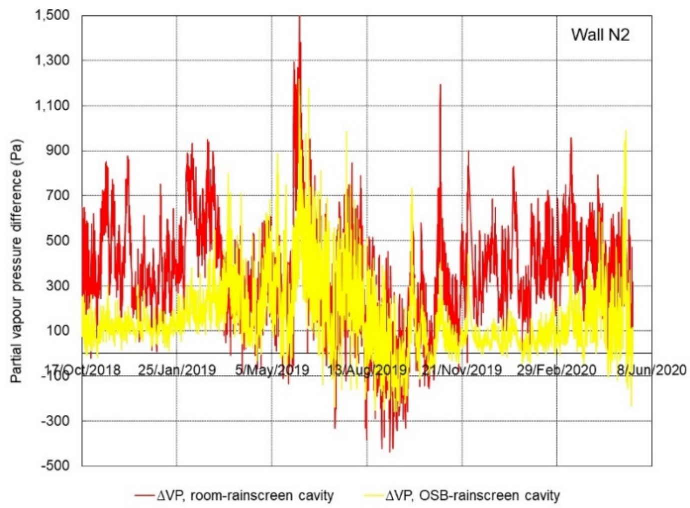


Figure 66. **Partial vapour pressure differences across north-facing wall panel N2**

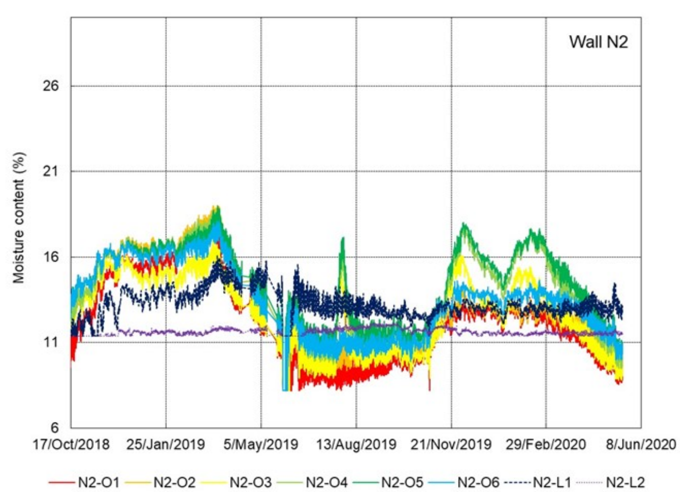


Figure 67. **Wood moisture content measurements from north-facing wall panel N2**

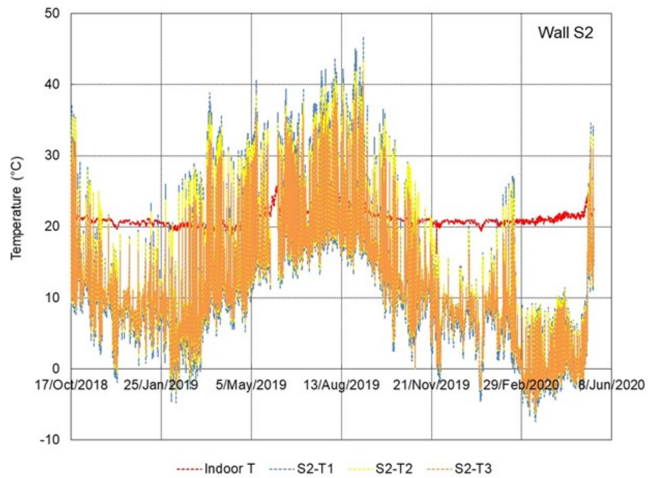


Figure 68. **Temperature profiles measured from south-facing wall panel S2**

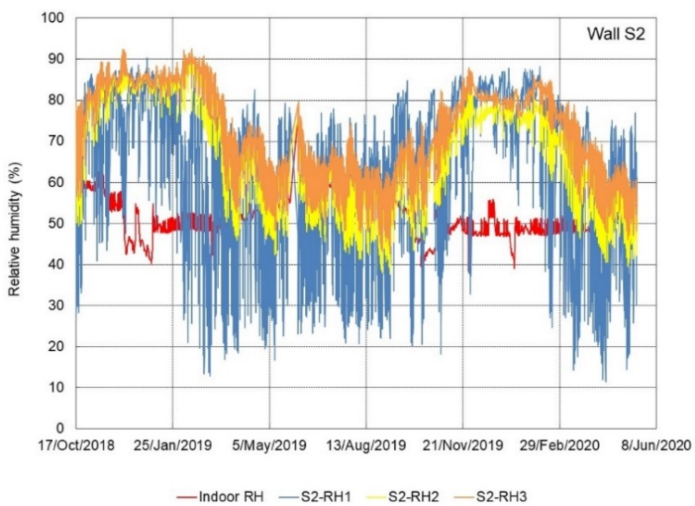


Figure 69. **Relative humidity profiles across south-facing wall panel S2**

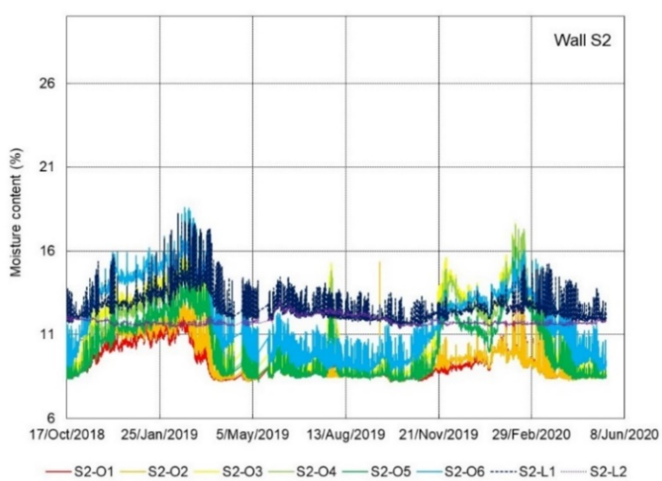


Figure 70. **Wood moisture content measurements from south-facing wall panel S2**

APPENDIX V: TEST RESULTS: WALL ASSEMBLY NO. 3

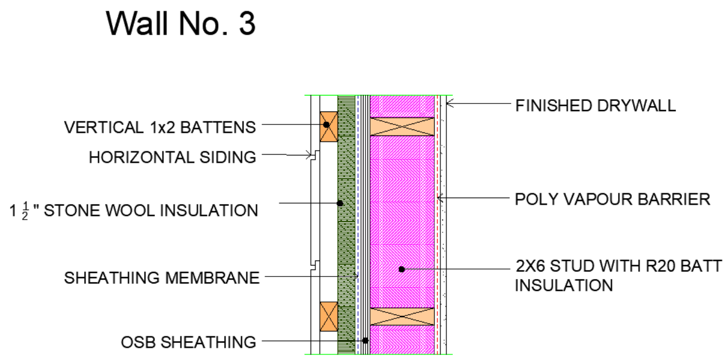


Figure 71. The wall assembly of wall assembly No. 3, with north-, south- and east-facing

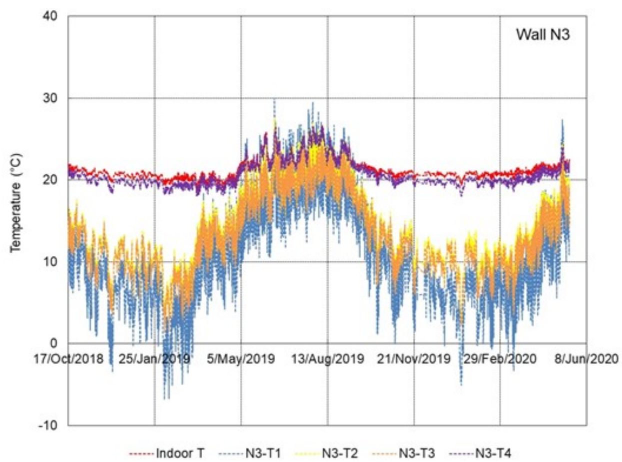


Figure 72. Temperature profiles measured from north-facing wall panel N3

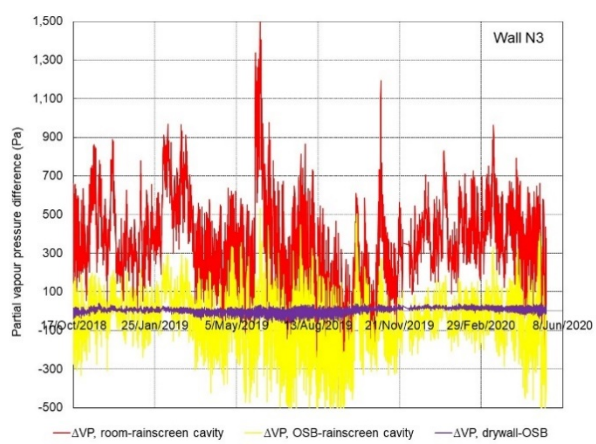


Figure 73. Partial vapour pressure differences across north-facing wall panel N3

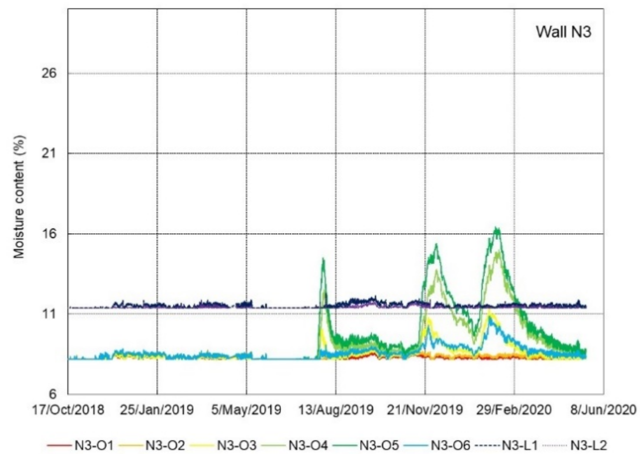


Figure 74. Wood moisture content measurements from north-facing wall panel N3

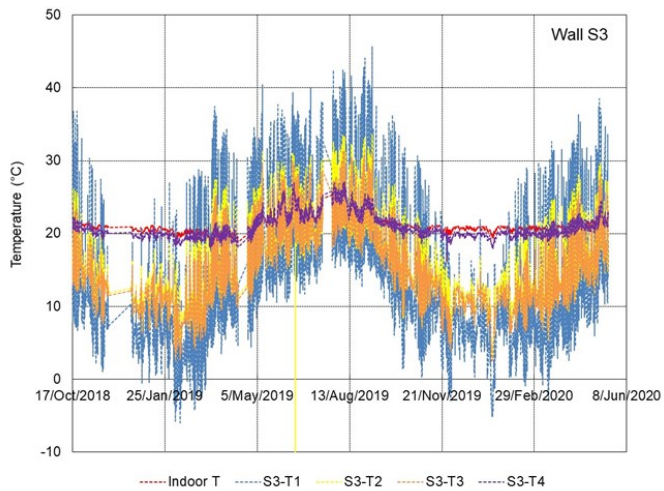


Figure 75. Temperature profiles measured from south-facing wall panel S3

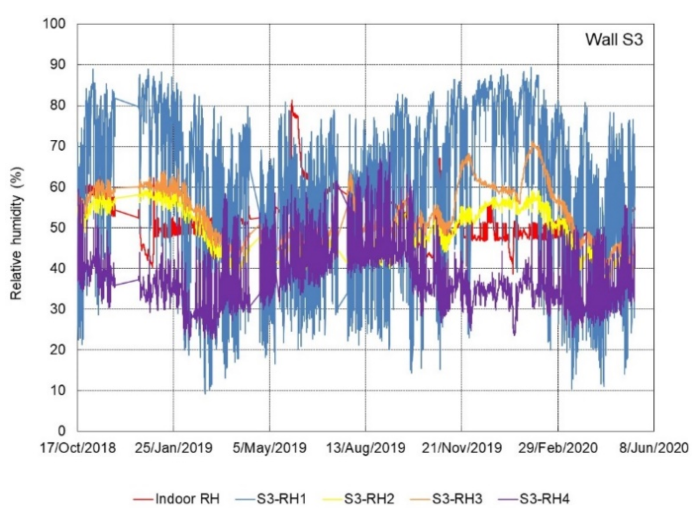


Figure 76. Relative humidity profiles across south-facing wall panel S3

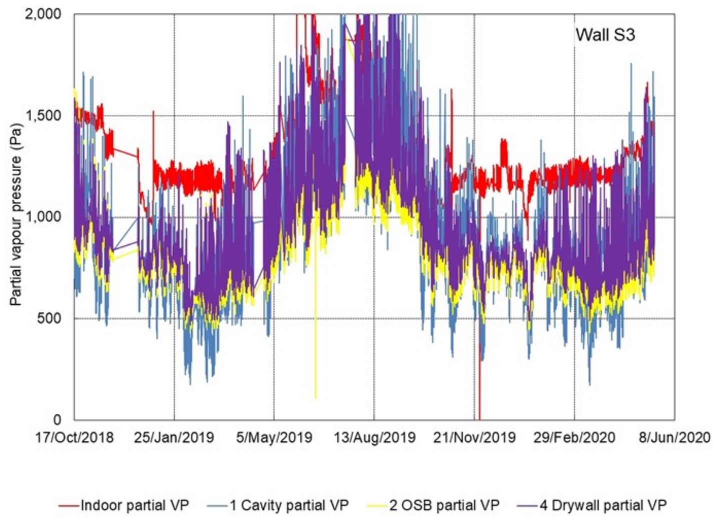


Figure 77. **Partial vapour pressures across south-facing wall panel S3**

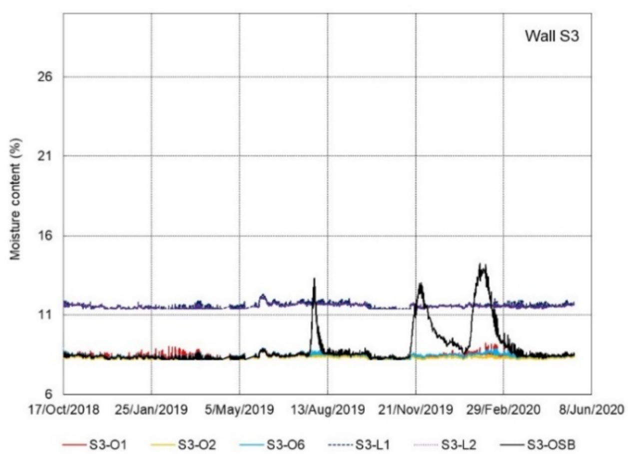


Figure 78. **Wood moisture content measurements from south-facing wall panel S3**

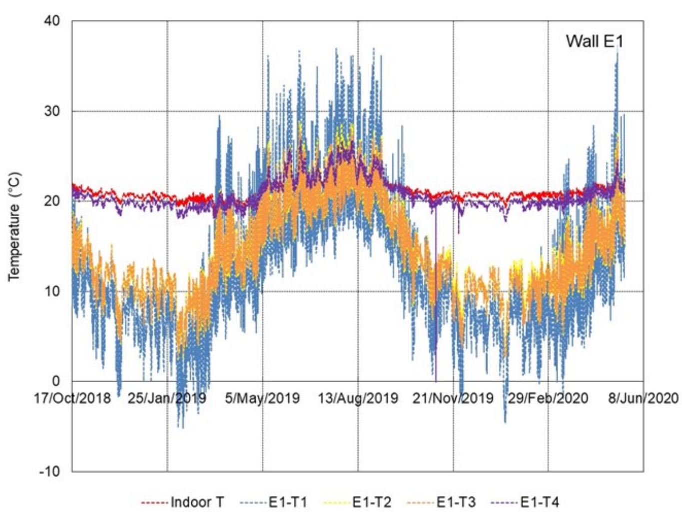


Figure 79. **Temperature profiles measured from east-facing wall panel E1**

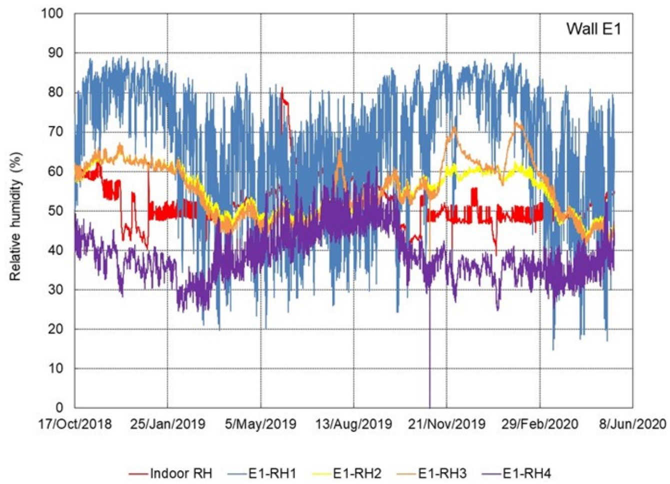


Figure 80. Relative humidity profiles across east-facing wall panel E1

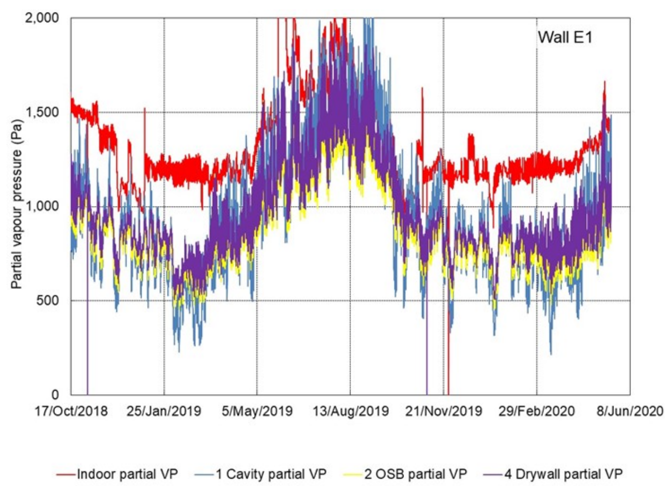


Figure 81. Partial vapour pressures across east-facing wall panel E1

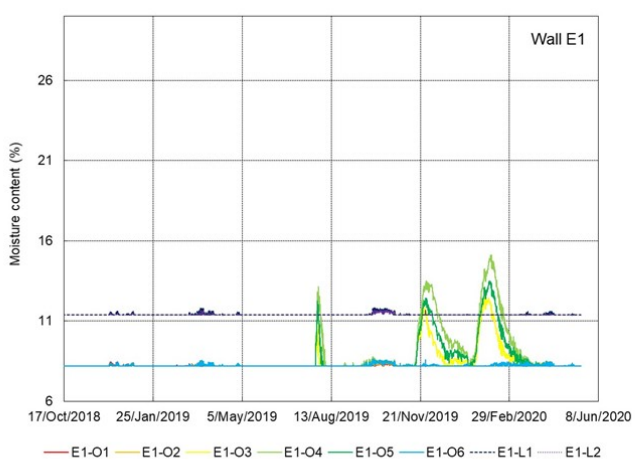


Figure 82. Wood moisture content measurements from east-facing wall panel E1

APPENDIX VI: TEST RESULTS: WALL ASSEMBLY NO. 4

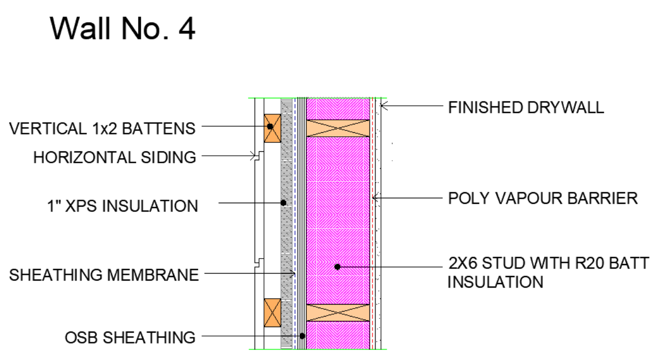


Figure 83. The wall assembly of wall assembly No. 4

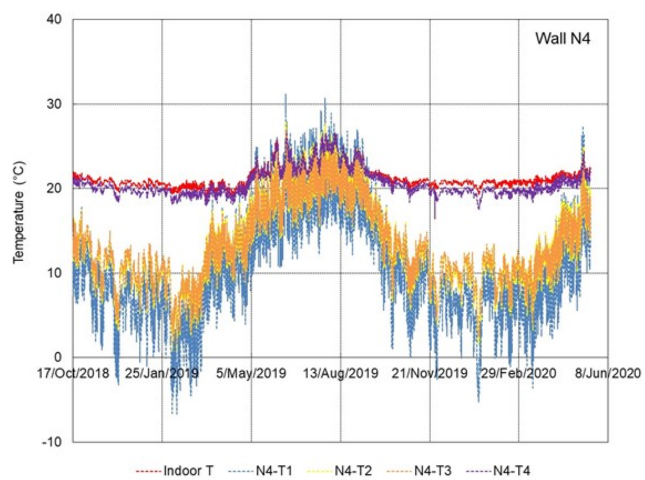


Figure 84. Temperature profiles measured from north-facing wall panel N4

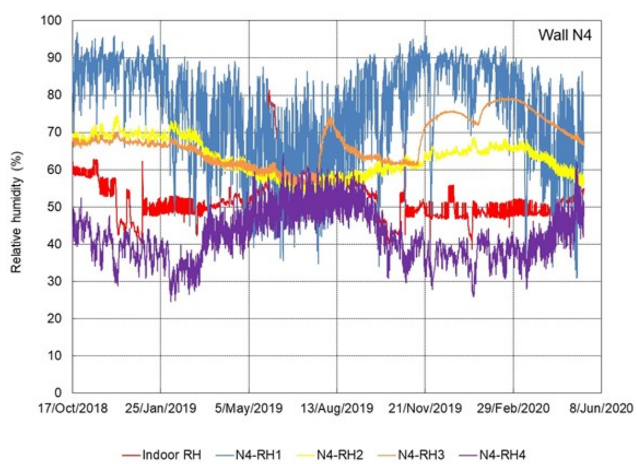


Figure 85. Relative humidity profiles across north-facing wall panel N4

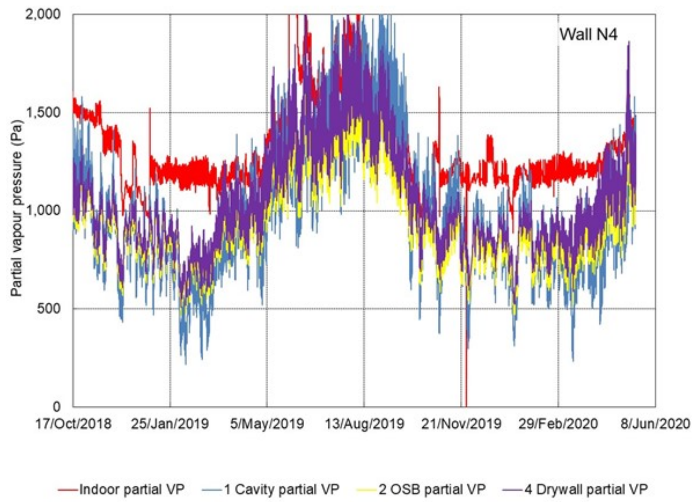


Figure 86. Partial vapour pressures across north-facing wall panel N4

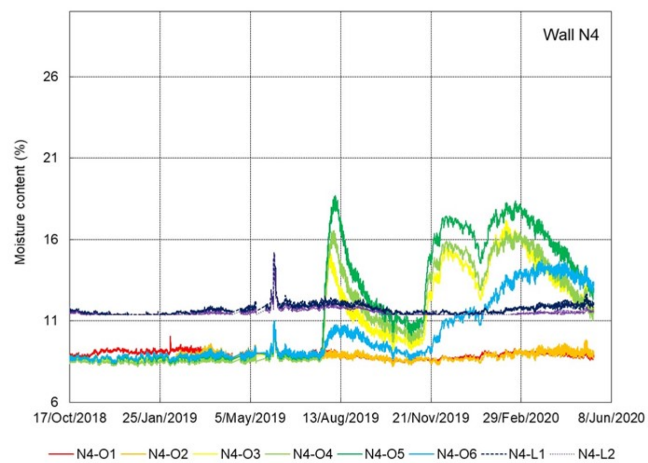


Figure 87. Wood moisture content measurements from north-facing wall panel N4

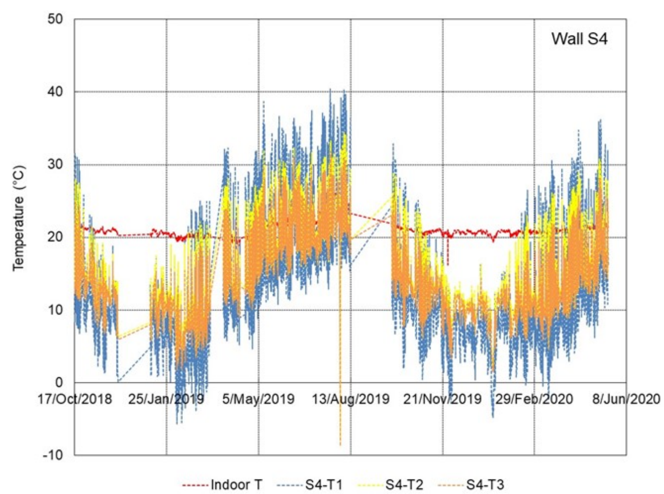


Figure 88. Temperature profiles measured from south-facing wall panel S4

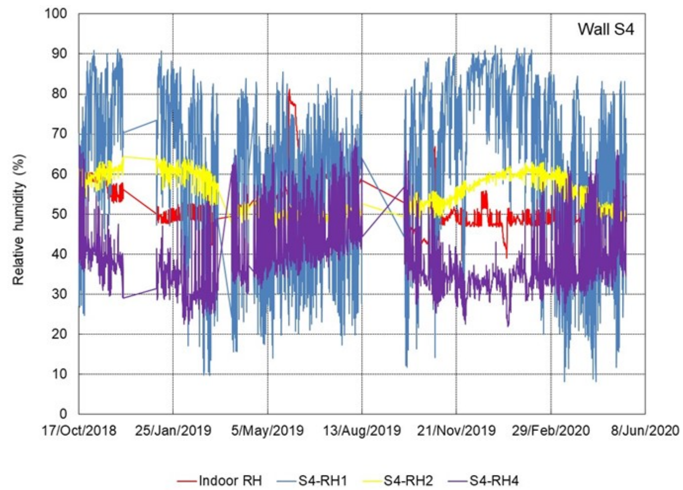


Figure 89. Relative humidity profiles across south-facing wall panel S4

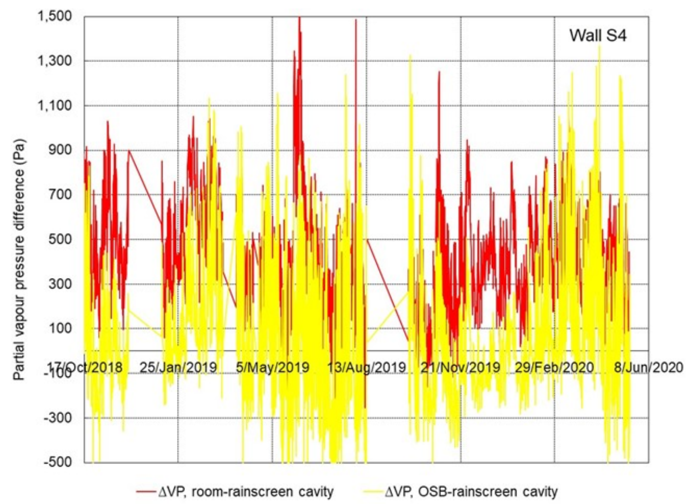


Figure 90. Partial vapour pressure differences across south-facing wall panel S4

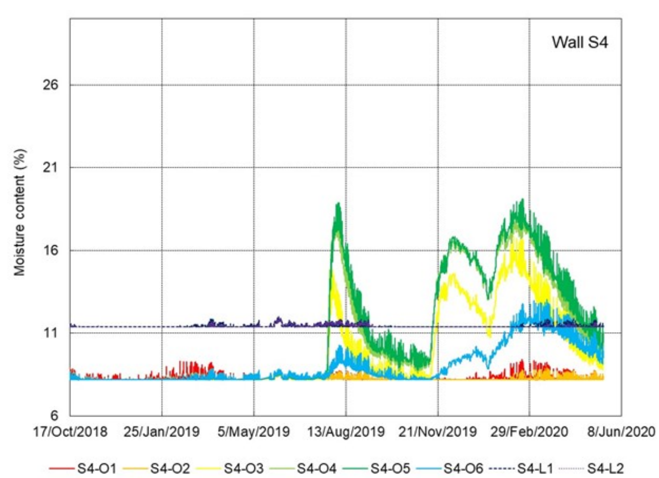


Figure 91. Wood moisture content measurements from south-facing wall panel S4

APPENDIX VII: TEST RESULTS: WALL ASSEMBLY NO. 5

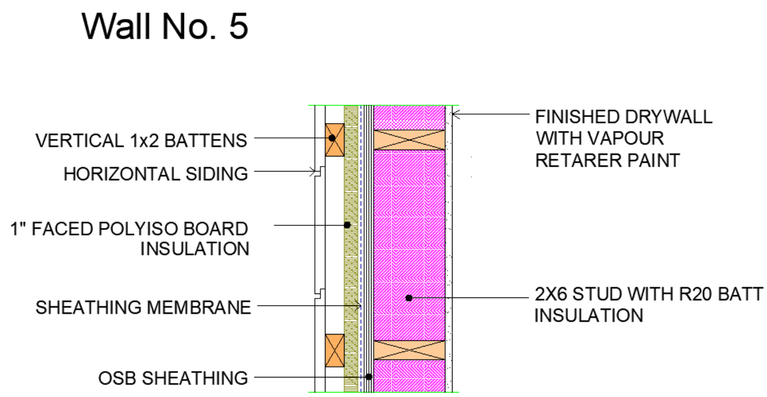


Figure 92. The wall assembly of wall assembly No. 5

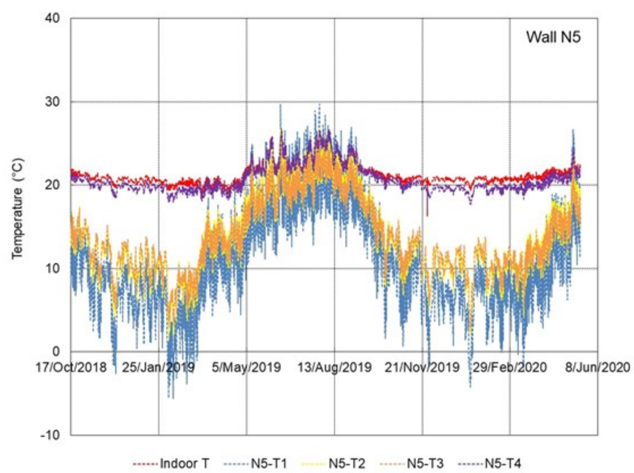


Figure 93. Temperature profiles measured from north-facing wall panel N5

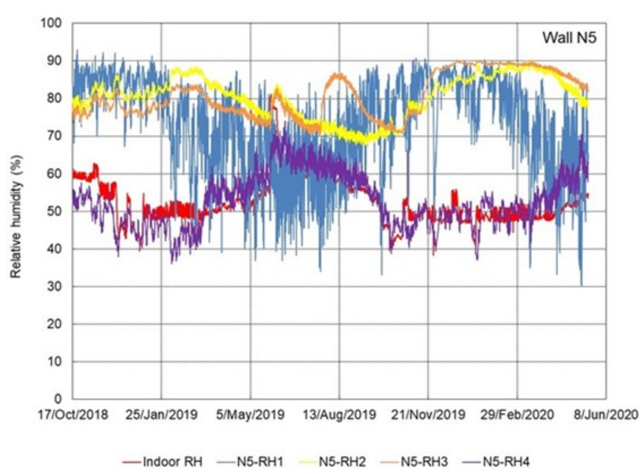


Figure 94. Relative humidity profiles across north-facing wall panel N5

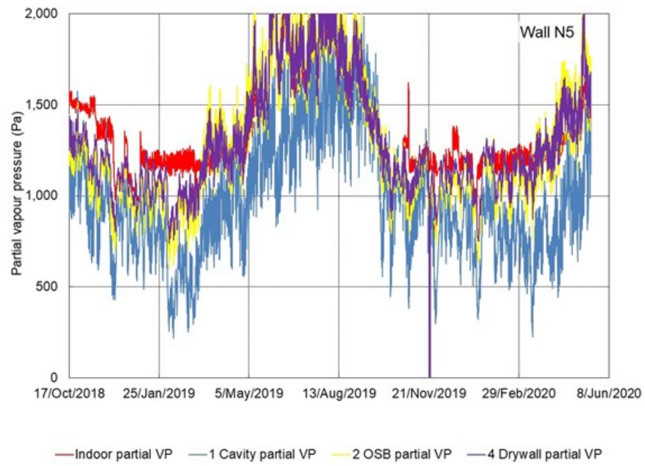


Figure 95. Partial vapour pressures across north-facing wall panel N5

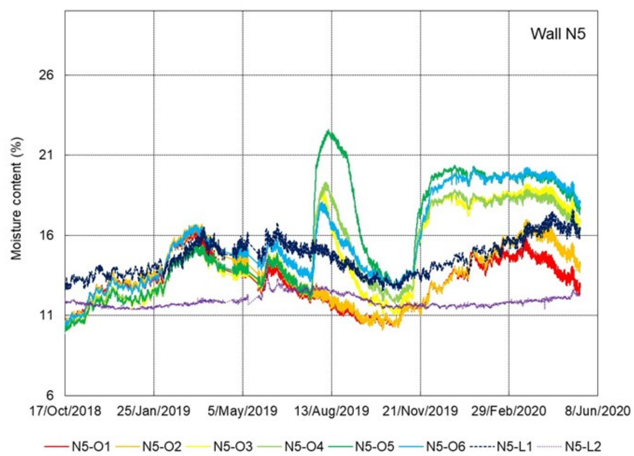


Figure 96. Wood moisture content measurements from north-facing wall panel N5

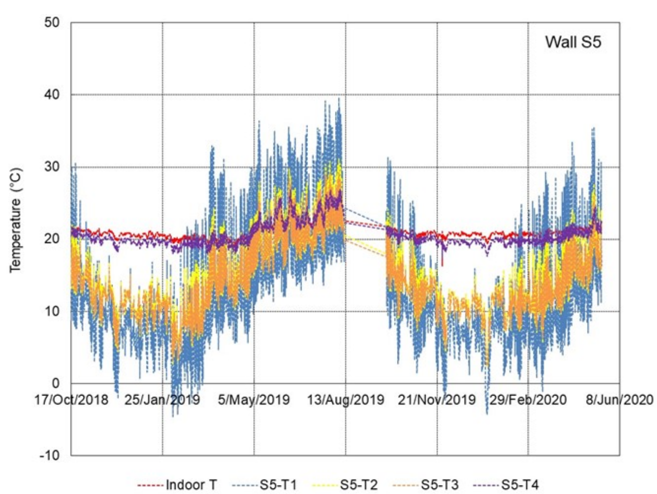


Figure 97. Temperature profiles measured from south-facing wall panel S5

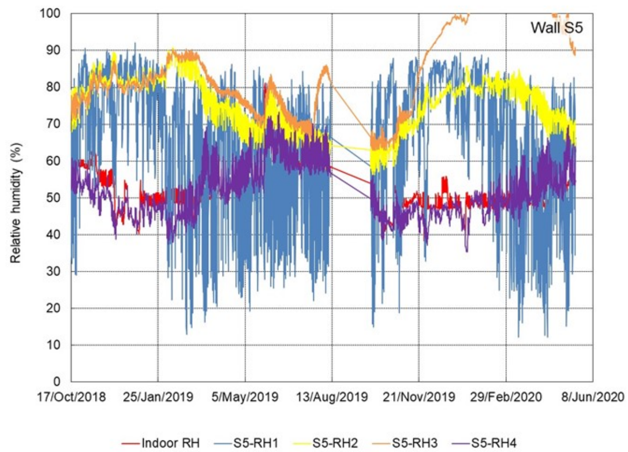


Figure 98. Relative humidity profiles across south-facing wall panel S5

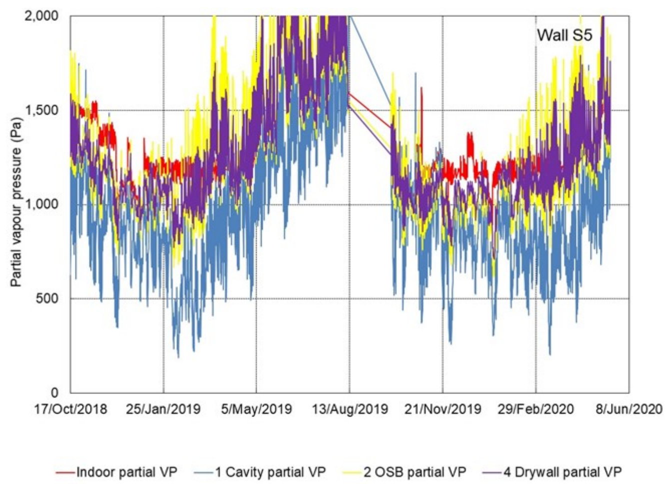


Figure 99. Partial vapour pressures across south-facing wall panel S5

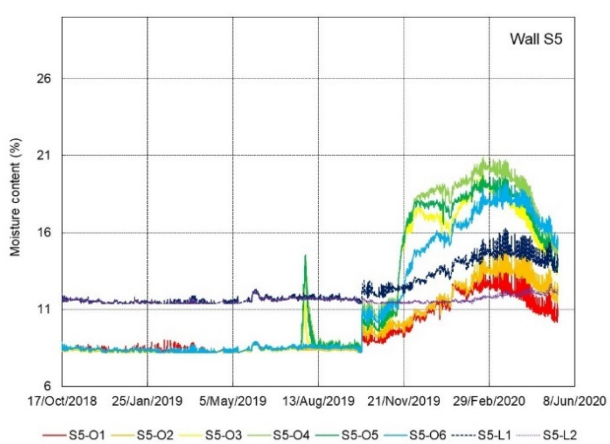


Figure 100. Wood moisture content measurements from south-facing wall panel S5

APPENDIX VIII: TEST RESULTS: WALL ASSEMBLY NO. 6

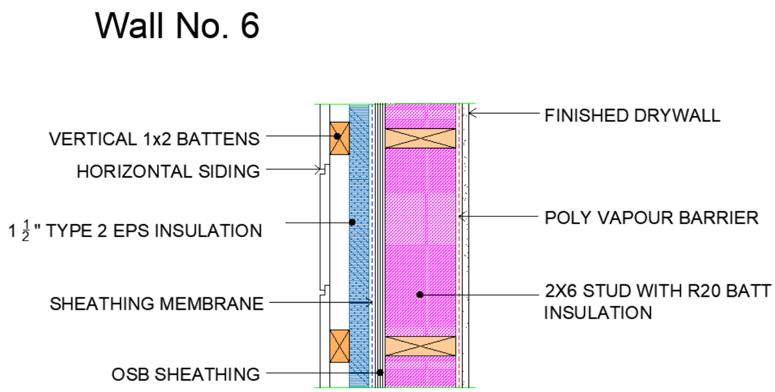


Figure 101. The wall assembly of wall assembly No. 6

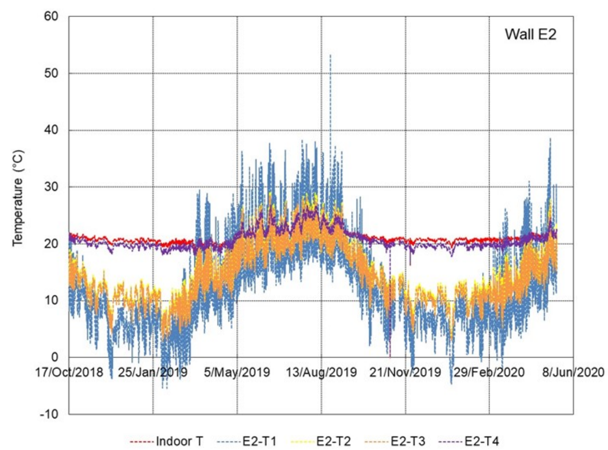


Figure 102. Temperature profiles measured from east-facing wall panel E2

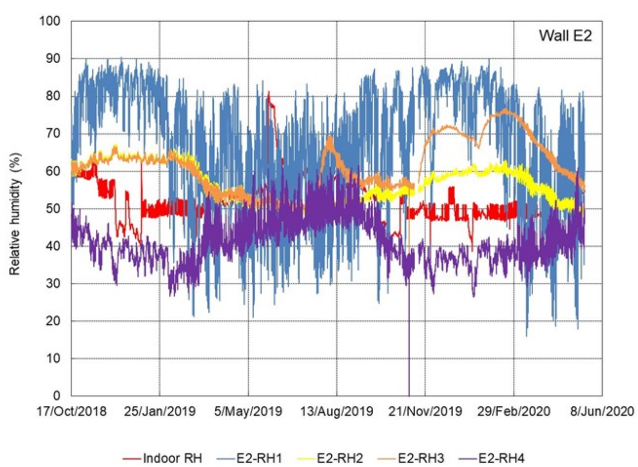


Figure 103. Relative humidity profiles across east-facing wall panel E2

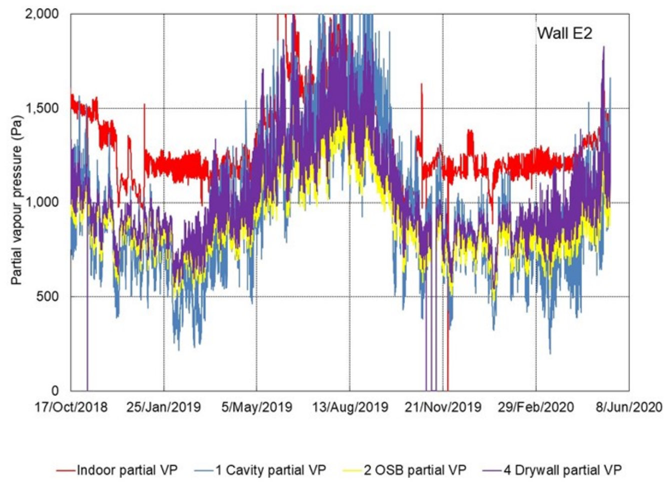


Figure 104. Partial vapour pressures across east-facing wall panel E2

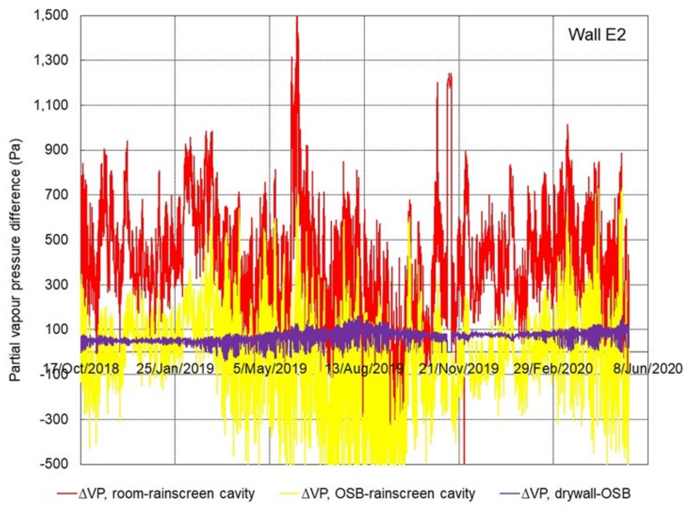


Figure 105. Partial vapour pressure differences across east-facing wall panel E2

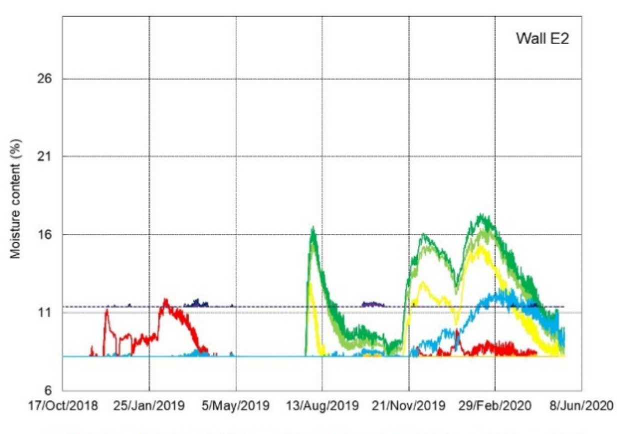


Figure 106. Wood moisture content measurements from east-facing wall panel E2

APPENDIX IX: OTHER TEST RESULTS

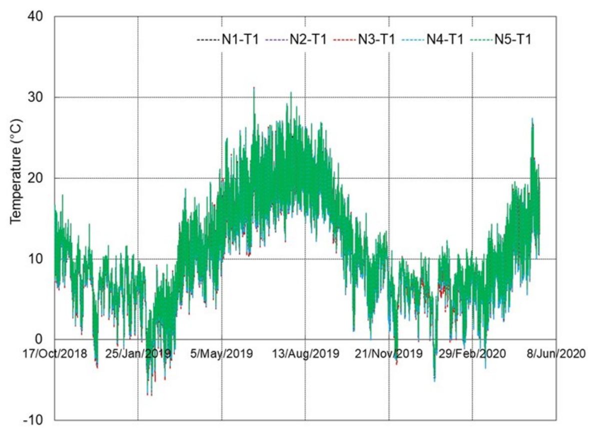


Figure 107. Measured temperature in the rainscreen cavities of the five north-facing walls

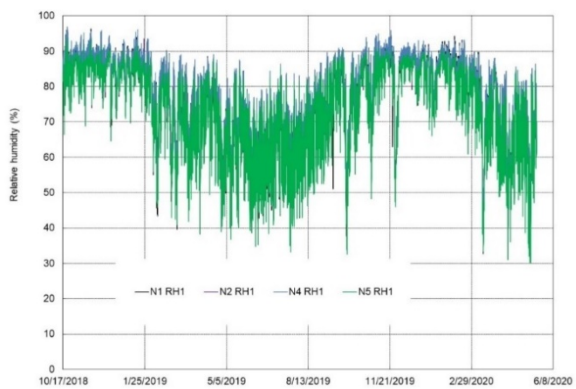


Figure 108. Measured relative humidity in the rainscreen cavities of the four north-facing walls (N3 RH1 missing due to malfunctioning sensor)

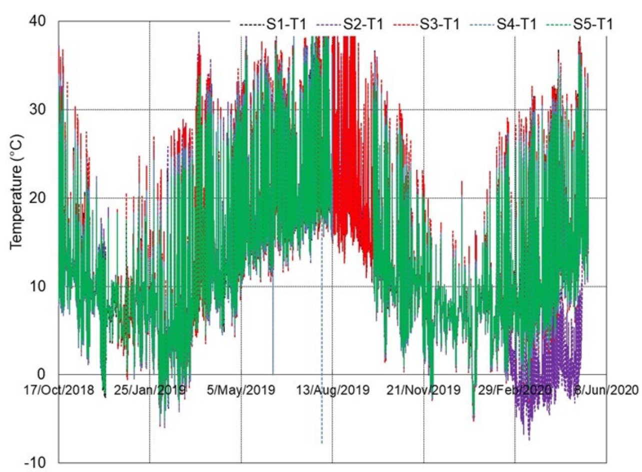


Figure 109. Measured temperature in the rainscreen cavities of the five south-facing walls

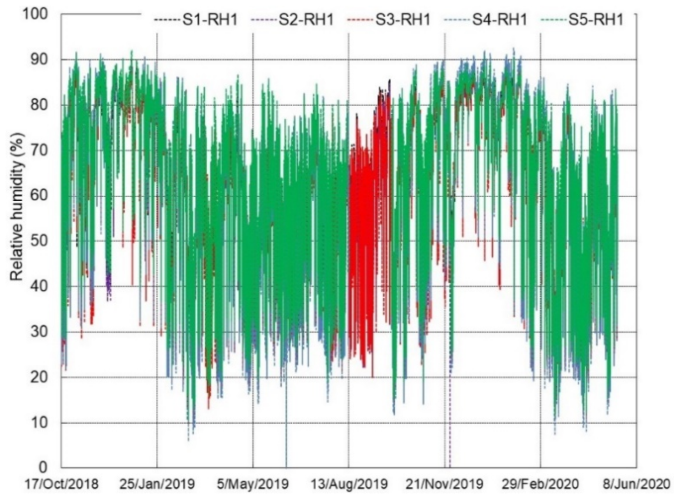


Figure 110. Measured relative humidity in the rainscreen cavities of the five south-facing walls

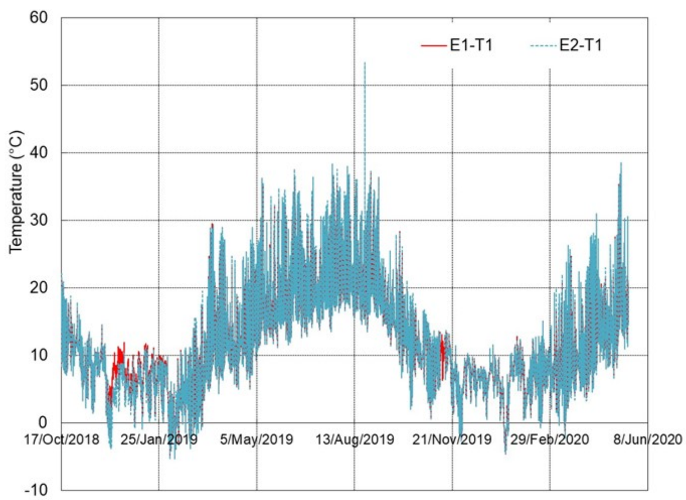


Figure 111. Measured temperature in the rainscreen cavities of the two east-facing walls

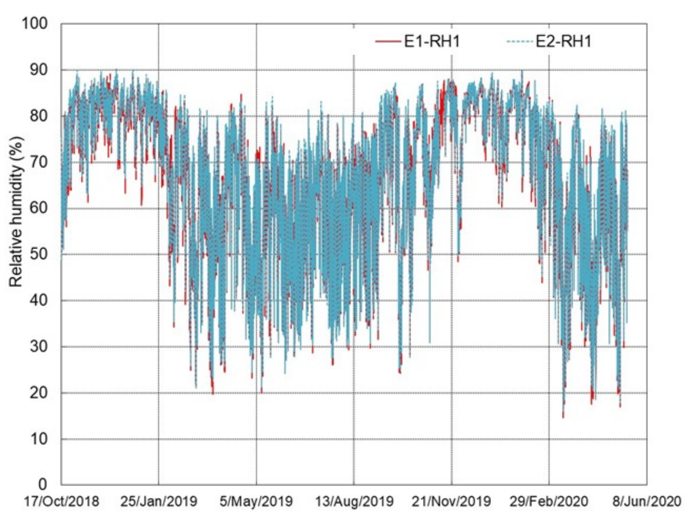


Figure 112. Measured relative humidity in the rainscreen cavities of the two east-facing walls

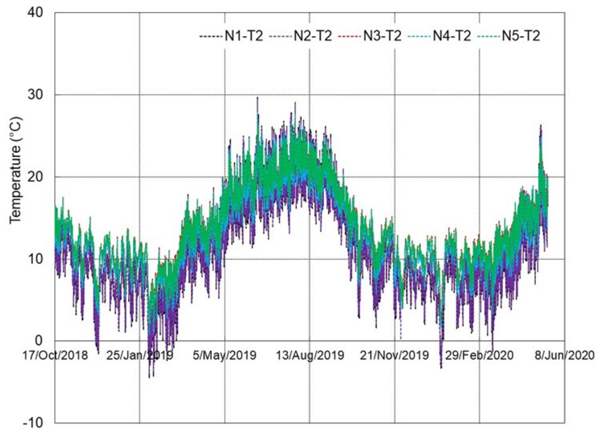


Figure 113. Measured temperature on interior surface (mid-height) of the OSB sheathing of the five north-facing wall panels

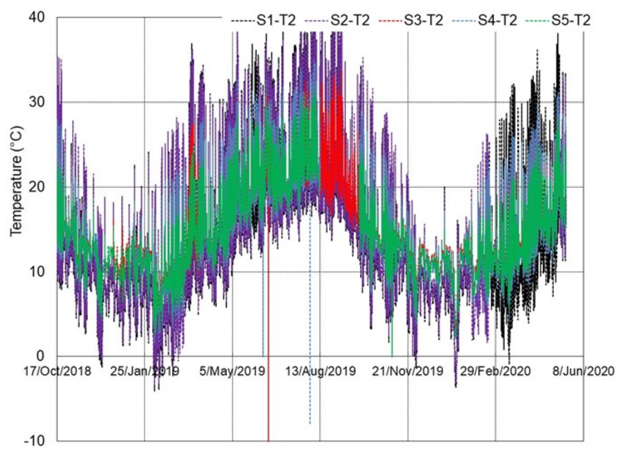


Figure 114. Measured temperature on interior surface (mid-height) of the OSB sheathing of the five south-facing wall panels

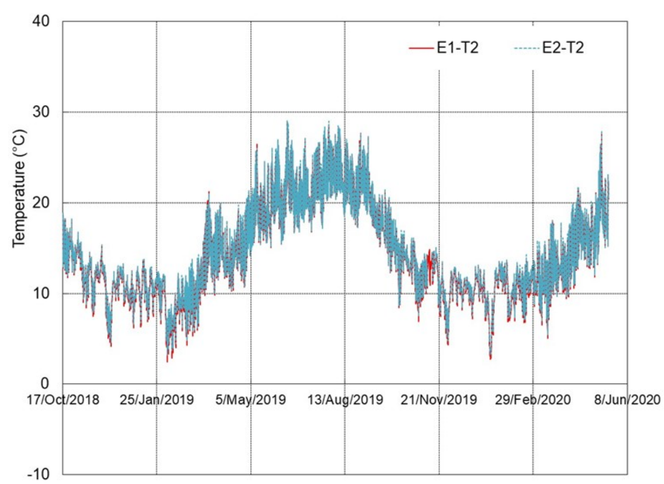
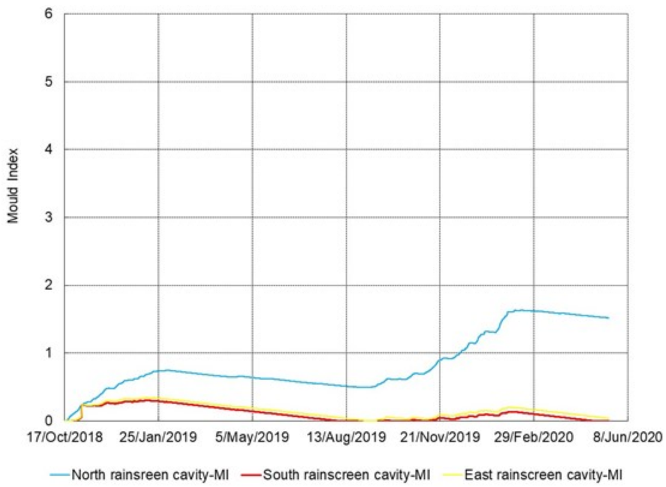


Figure 115. Measured temperature on interior surface (mid-height) of the OSB sheathing of the two east-facing wall panels



MI calculated based on the average temperature and relative humidity of the measurements (i.e., T1, RH1) from the rainscreen cavities

Figure 116. Calculated ASHRAE 160 (2016) Mould Index (MI) for OSB sheathing for walls in the North, South and East orientations

Panel N1 **Panel N4** **Panel S5**

Figure 117. Visual condition of OSB sheathing of selected wall panels at the completion of testing in July 2020

APPENDIX X:MEASURING WOOD MOISTURE CONTENT AND ADDITIONAL INFORMATION OF SENSORS

Measuring Wood Moisture Content (MC)

There are two major considerations when measuring wood MC. For an electrical resistance-based measurement method, it is important to note that the best accuracy is in the range from 6% to 25%. It is difficult to measure a very low MC when the electrical resistance of the (dry) wood is too high. It is also challenging to measure a MC close to or higher than the fibre saturation point (indicating saturation of bound water in cell walls, with 30% MC on average for most wood species), since free water in cell lumen has little effect on the electrical properties (FPL 2010). A previous calibration study indicated that such measurement methods overall had acceptable accuracy (defined as about ±2% MC) for Douglas fir and S-P-F solid wood and OSB under typical ambient conditions (Wang and Thomas 2018) within this MC range. In addition to the basic factors that should be corrected in the MC readings (see section 4.3), such as wood species and temperature, the measurement of MC of wood-based composites and treated wood using the resistance-based method is also influenced by chemicals, such as adhesives, preservatives, and fire retardants. For example, measuring the MC of plywood may have measurement errors caused by the phenol-formaldehyde adhesive, which is often coupled with sodium hydroxide to accelerate curing of the adhesive (Boardman et al. 2011; Wang and Thomas 2018). Compared to plywood, more consistent and reliable measurements can be established to support resistance-based MC measurements in OSB. A calibration equation has been reported by the US Forest Products Laboratory, based on large amounts of specimens with different sources (Boardman et al. 2017).

Another important factor that should be taken into consideration is the MC gradients inside the wood and selection of the most appropriate locations (or depths) for measurements when MC gradients are anticipated. Wood, particularly in large sizes, has delayed responses to changes in its environmental conditions and there are always moisture gradients inside a wood member under fluctuating environmental conditions. The surface responds more quickly; but the core tends to remain at a more stable MC, being insulated by the surface layer (Sundström et al. 2011; Wang 2018). For measuring MC of the OSB sheathing in this study, the uninsulated moisture pins are installed from the interior surface to the mid-depth point (about 6 mm)[16]. Such a measurement is expected to take time to respond, also in a lower magnitude in MC changes when the exterior surface of the OSB sheathing becomes wet due to water injection or localized vapour condensation. Examining the responses of the test walls to the three phases of water injection in this test, it is found that the delay is about 1-2 days for the MC measurements to show elevation after start of each phase of water injection. This should be the time for the water first to transfer from the wetting pad to the OSB, and then distribute through half thickness of the OSB sheathing.

[16] It is important to note that the source of liquid water is anticipated to primarily come from the exterior side of the OSB sheathing through intentional water injection. This is an important consideration given that uninsulated pins are being used and the increased conductivity will be due to moisture reaching the tips of the pin.

Additional Information of Sensors

Table 6. Sensors installed in the test wall panels

Purposes	Instrument	Shape and size	Note
Measuring environmental relative humidity (RH) and temperature (T)	Combined RH and T sensors, called “RH/T” sensors	Small probes	RH resolution: 0.5%; Accuracy: ±3% to ±5% (in the range of 10-95%) Temperature tolerance: 1%; Resolution: 0.1°C; Accuracy ±1°C
Measuring wood MC	Resistance-based moisture pin sensors	Small screws	Each sensor is compensated for temperature and wood species
Measuring air flow in rainscreen cavity	Remote head air velocity sensor	Small probe	Velocity range: 0.15 m/s to 20 m/s, with repeatability within 1%
Collecting and transferring data wirelessly	Data loggers, wireless module	Data logger box: 125 mm × 125 mm × 64 mm	The device also integrates an RH/T sensor for measuring the temperature and RH on the top of each wall.

Table 7. Sum of sensors installed inside the 12 test wall panels

RH/T sensor	Moisture sensor	Air flow sensor	In total
58	96	1	155

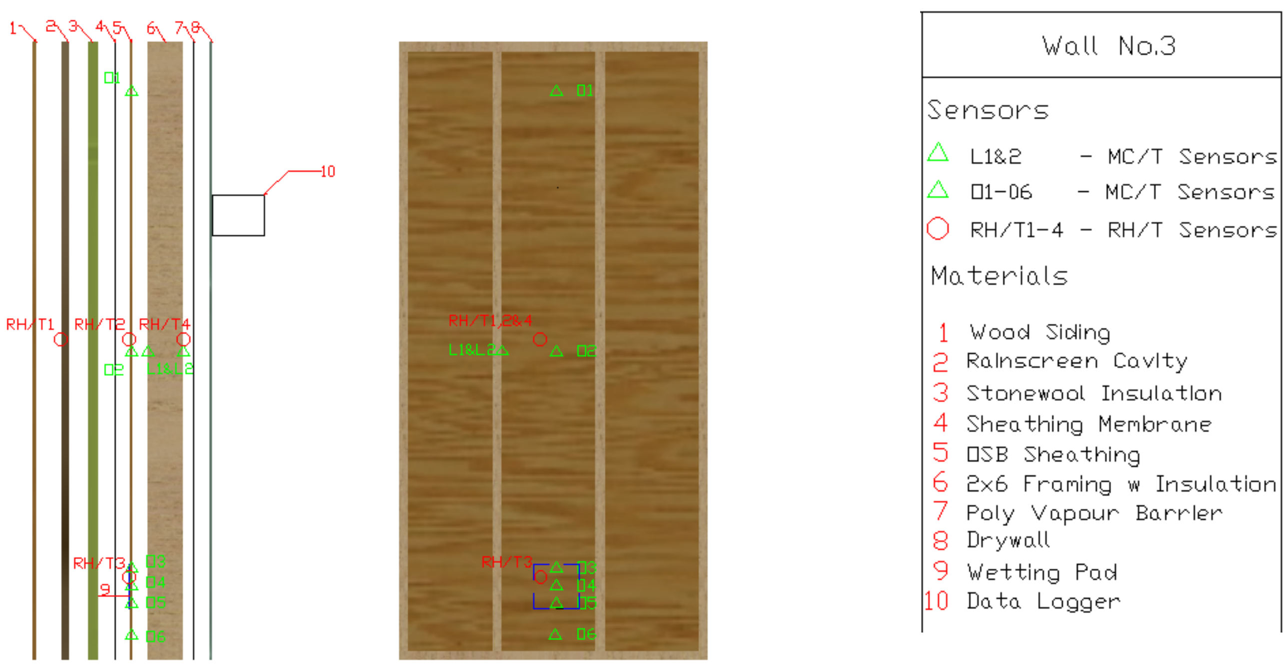


Figure 118. A schematic to show locations of sensors in a wall assembly No. 3

APPENDIX XI: PICTURES TAKEN DURING CONSTRUCTION AND DECONSTRUCTION

Figure 119. A double-stud wall with a 6 mm gap between the two rows of studs

Figure 120. A paper towel together with a plastic tube installed on the exterior surface of the OSB sheathing for injecting water in the future

Figure 121. The perimeter of each wall opening pre-sealed with membranes, with gasket installed at the bottom

Figure 122. An RH/T sensor installed in the rainscreen cavity, being exterior to the exterior stone wool insulation

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