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Measured Drying Ability of Compact Low-Slope Roofs

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Abstract

In conventional compact low-slope roofs, insulation is sandwiched between two vapour-impermeable layers: on top, the roof membrane, and underneath, the concrete deck or metal deck (with an additional air- and vapour-retarding membrane). This approach can be problematic should water get into the roofing assembly—either during construction, due to a roofing membrane leak, or from air leakage from the interior.

RDH Building Science Laboratories recently completed Phase 1 of an experimental program involving three compact low-slope roof assemblies on metal decks that were constructed side by side in a field exposure facility in Waterloo, Ontario (Climate Zone 5-6). One assembly was constructed as a reference or base case, with two vapour barriers. The two other assemblies were designed and constructed to allow drying by vapour diffusion to either the top or bottom side. All three assemblies were subjected to periodic wetting by the injection of controlled amounts of water, and moisture movement was tracked using embedded moisture, temperature, and relative humidity sensors. It was found that the roof assembly with a high-vapour-permeance membrane on the metal deck (i.e., the inward drying assembly) was most effective in drying water following each intentional wetting. Implications for design and construction will be discussed.

Speaker

Jonathan Smegal — RDH Building Science Laboratories

JONATHAN SMEGAL is an associate at RDH Building Science, where his work includes both laboratory research and assessment of building performance in the field. In the lab, he has conducted research on cladding deflection, drainage and drying in wall assemblies, and specialized water-uptake and vapour-permeance testing. In the field, he is involved with design review, new construction site audits, and forensic investigations of water ingress, indoor air quality, and mold. Smegal is a frequent speaker at industry events and has authored or coauthored multiple peer-reviewed conference papers on vapour drives, moisture management, and other building science topics.

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Measured Drying Ability of Compact Low-Slope Roofs

INTRODUCTION

Roofs have unique challenges in terms of water and moisture control during and after construction. The typical cold-climate commercial low-slope (flat) roof system consists of insulation encapsulated between a low-permeance roofing membrane on the exterior and a vapour barrier on the interior. The deck-level vapour barrier may be required in cold climates (to control vapour diffusion), but corrugated metal roofing decks and poured concrete decks also have low vapour permeance and are installed in most roofs in all climate zones. Low-permeance encapsulation can be problematic if water gets into the insulation layer, which can happen in one or more of the following ways:

1. During construction, precipitation can be trapped on top of the air/vapour barrier or within the insulation layer(s).
2. In service, precipitation may leak past the roofing membrane. Roof investigations have identified many different leakage paths. For example, parapet details, mechanical or structural penetrations in the roof membrane, skylight or clerestory window details, and imperfect membrane laps can all result in water leaking past the roof membrane (i.e., the water control layer).
3. In some climates—particularly cold climates—air leakage condensation into the roofing assembly from the interior can lead to moisture accumulation in the roofing insulation and coverboard.

In many cases, when some of the roof becomes wet, the solution is to remove all of the insulation and reconstruct the entire roof, resulting in significant amounts of wasted insulation, construction materials, and associated costs.

OBJECTIVE

As traditional low-slope roofs are unable to dry any water trapped between the two vapour-impermeable layers, the addition of inward drying was proposed as a means to increase the long-term durability and sustainability of low-slope roofs. So-called "self-drying roofs" have been studied extensively in the past (Tobiasson, 1983; Desjarlais, 1995; Desjarlais et al., 1998; and Karagiozis, 2002), but modern materials such as stone wool insulation and moisture-adaptive vapour control layers offer new potential.

A research program was developed with the objective of quantifying the performance of three roofing systems with different approaches to drying when exposed to field conditions. One was constructed as a traditional industry-standard roof assembly, and two were constructed with some drying capacity designed into the assembly. The roof assemblies were compared under normal operating conditions and with controlled wetting events with a known amount of water injected into the roof assembly at a known location.

SCOPE

This analysis will focus on the performance of commercial low-slope roof assemblies constructed of a metal deck, direct-applied air barrier, vapour- and air-permeable stone wool roofing insulation, and a two-ply modified-bitumen torched-down roofing membrane. The conventional low-slope roofing assembly with a self-adhered air/vapour barrier applied directly to the deck will be compared to two alternative roofing designs as follows:

1. A smart vapour barrier was installed over the steel deck to allow drying of water in the roofing assembly to the interior space. The term "smart vapour retarder" is used as a generic term and further defined below.
2. A vapour diffusion port was installed on the exterior of the roofing assembly to allow drying of water in the roofing assembly to the exterior environment.

Smart vapour barriers (or retarders) are membranes whose vapour permeance changes depending on the conditions they are in. In an environment with lower relative humidity (RH), such as the interior of a typical cold-climate wall assembly, they have a low vapour permeance that stops interior moisture from moving outward towards the colder sheathing. In a higher-RH environment, such as the interior of a roof or wall that has experienced wetting and elevated moisture, the membrane would become more vapour-permeable and allow the elevated moisture to dry. Smart vapour barriers have been studied elsewhere as an aid to drying moisture from low-slope roofs (Geving et al., 2013).

Venting of moisture from low-slope roofs has been studied and practised for years (Baker, 1976; Geving and Holme, 2010; Karagiozis et al., 2002; Tobiasson, 1983), and the need to ensure the vents are airtight has been clearly demonstrated. Vapour diffusion drying through small areas (vapour diffusion ports) has been proposed as a solution.

The roofing assemblies are explained in more detail under "Construction and Instrumentation" below. The research program ran from December 15, 2015, to September 14, 2017, and all of the data are included in this analysis.

APPROACH

The intent is to use measured data to understand the drying capacity of current construction methods compared to the two methods hypothesized to improve drying. The performance of the roof assemblies will be compared using the following data:

- RH sensor measurements at various locations within the roofing assembly, under normal operating conditions and immediately following intentional wetting events
- Wood moisture-content sensor measurements using wood wafer sensors in the roofing assembly, under normal operating conditions and following intentional wetting events

Water was injected into the roofing assembly using plastic tubing and water storage media to simulate controlled

Roof Panel	Structure	Air/Vapour Control	Thermal Control	Water Control	Notes
1	Metal roofing deck	Self-adhered air/vapour barrier 1.7 ng/Pa·s·m^2 (0.03 perms)	2 layers of 3-in. stone wool	2-ply mod-bit roofing	Diffusion roof vent installed
2	Metal roofing deck	Self-adhered air/vapour barrier 1.7 ng/Pa·s·m^2 (0.03 perms)	2 layers of 3-in. stone wool	2-ply mod-bit roofing	None
3	Metal roofing deck	Smart vapour control 37 ng/Pa·s·m^2, (0.6 perms) and 925 ng/Pa·s·m^2, (16 perms)	2 layers of 3-in. stone wool	2-ply mod-bit roofing	None

Table 1 – Roofing study experimental construction variables.

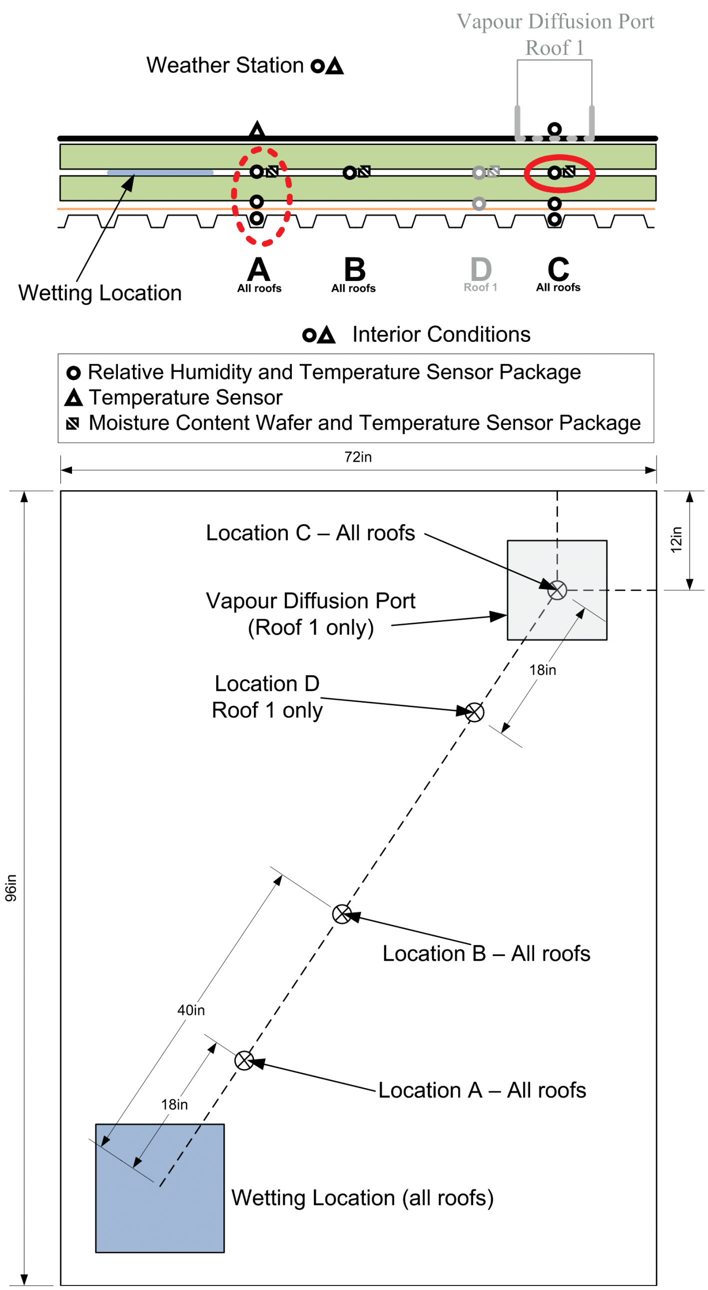


Figure 1 – Schematic of test roof assemblies with sensors and dimensions. Roof Panel 1 includes a vapour diffusion port and contains extra sensors at Location D and within the vapour diffusion port.

wetting events of a known volume at a known location (see “Enclosure Wetting Systems,” below).

RESEARCH FACILITY

The test roofs were constructed on the RDH Building Science Laboratories test hut outside of Waterloo, Ontario. This area has just more than 4000 HDD18 (heating degree days based on 18°C), which places it near the boundary of International Energy Conservation Code (IECC) Climate Zones 5 and 6. The region generally experiences cold winters and hot summers, so both heating and cooling loads are expected over the course of the year. The test hut location is in a rural area, not shaded by taller buildings or obstructed from prevailing northern winds.

The test hut is a 180-sq.-ft. (20 ft. x 9 ft.) (6 m x 2.7 m) field exposure facility with the capability of monitoring four full-scale test walls on two orientations, and three 48-sq.-ft. roof panels, each measuring 6 x 8 ft. (1.8 m x 2.4 m). This building permits all of the roof test panels to be exposed to the same interior and exterior conditions in a side-by-side installation. The test hut is mobile, and hence can be relocated to any location and reoriented easily on site.

CONSTRUCTION AND INSTRUMENTATION

The construction of the three roof panels is summarized *Table 1*. The water control layer (uppermost roofing membrane) on the roof assemblies is a two-ply modified-bitumen roofing membrane, and the thermal control layer is two layers of 3-in. stone wool. A stone wool insulation with an asphaltic coating was installed as the top layer so that the roofing membrane could be directly torched to it. The air and vapour control is the deck-level membrane in each roof panel. Roof Panel 1 was constructed with a vapour diffusion port installed onto the roofing membrane (see *Figure 1*).

For Roof Panels 1 and 2, the deck-level air and vapour control is self-adhered air- and vapour-impermeable membrane. Roof Panel 3 uses a sheet-applied smart membrane, which has a vapour permeance that varies with surrounding RH with an ASTM E96 dry cup Sd value of 5 m (37 ng/Pa·s·m^2, 0.6 US perms) and a wet cup Sd value of 0.2 m (925 ng/Pa·s·m^2, 16 US perms). It is likely that the vapour permeance would increase even further with RH increases beyond the wet cup test conditions of 50% RH on one side and 100% RH on the other side of the test sample, but this range is not as typical for testing or reporting. The structure and interior finish are corrugated 20-gauge galvanized metal roof deck for all three roof assemblies.

Typically, in high-performance roofing design, a board substrate fastened to the metal deck is recommended to support the deck-level air (and optionally, vapour) control layer. This provides rigidity to

Figure 2 – Installed wetting system with water storage medium and injection tube.

the air barrier membrane so it is not easily damaged, and even where it is damaged, the sheathing transfers the air barrier around any penetrations in the membrane so that continuity is ensured.

However, in many roofing assemblies, the sheathing, and even the air barrier, is value-engineered out of the design. The membrane is applied directly to the metal deck and inevitably becomes filled with holes during construction. This can be critical to performance in some buildings if air from the interior leaks into the roofing insulation between the vapour barriers. During construction of this research project, no holes were placed in the metal deck; however, metal roof decking installed in real buildings is typically punctured. Metal decking also has seams that are not filled to stop air/vapour movement. Flutes in the deck can be continuous for long distances across the roof, connecting the interior spaces to the entire length or width of the roof through holes in the metal deck. Piñon and LaTona (2013) conducted research including both laboratory testing and theoretical calculations to determine the effective vapour permeance of a steel deck with typical construction-related penetrations. Based on that previous research, holes were drilled in the metal deck for the current research program to allow some natural air/moisture movement. Specifically, 3/16-in. (4.7-mm) holes were drilled 10 in. (254 mm) o.c. on the lower side of every metal deck flute in each test roof. The holes were intended to meet a 0.04% free area to achieve a vapour permeance of approximately 1 US perm (57 ng/Pa·s·m^2).

ASTM E96 wet cup testing was conducted in the laboratory to determine the effective vapour permeance of the holes in the metal deck. A layer of high-vapour-permeance house wrap was used as an air barrier so air could not pass directly from the 100% RH environment to the laboratory space. The metal deck with holes was tested three times, and the range in measured vapour permeance of the three measurements was between 1.1 and 1.4 US perms (63 and 80 ng/Pa·s·m^2).

A wetting system was installed in each of the roof assemblies as shown by the blue squares in the schematic drawing (*Figure 1*) and in the installation photo (*Figure 2*). The wetting system allowed a controlled amount of water to be injected to a controlled location, simulating a roof leak or construction moisture between the layers of stone wool insulation. The objective of injecting water into the roof assembly is to determine the redistribution of the moisture and to determine the relative drying ability between the different roof assemblies. The wetting events were conducted for five days each, starting June 6, 2016; October 17, 2016; and June 26, 2017.

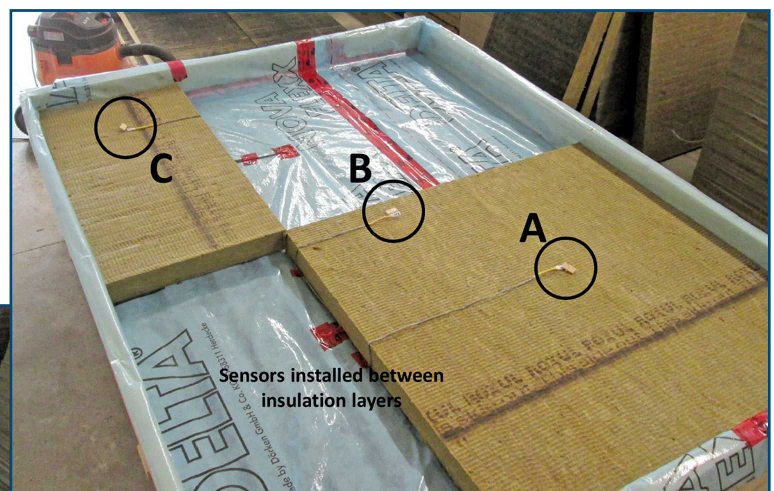


Figure 4 – Roof Panel 3 RH, wood moisture-content wafers and temperature sensors installed on first layer of insulation. Wetting system not yet installed.

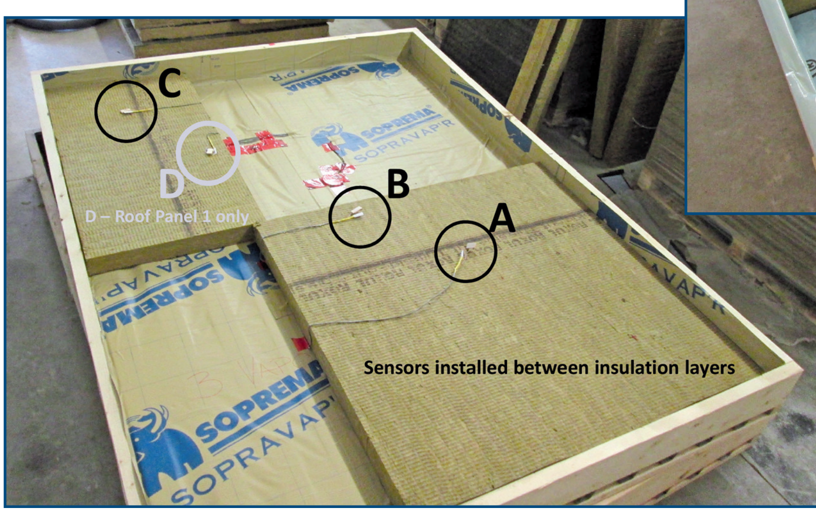
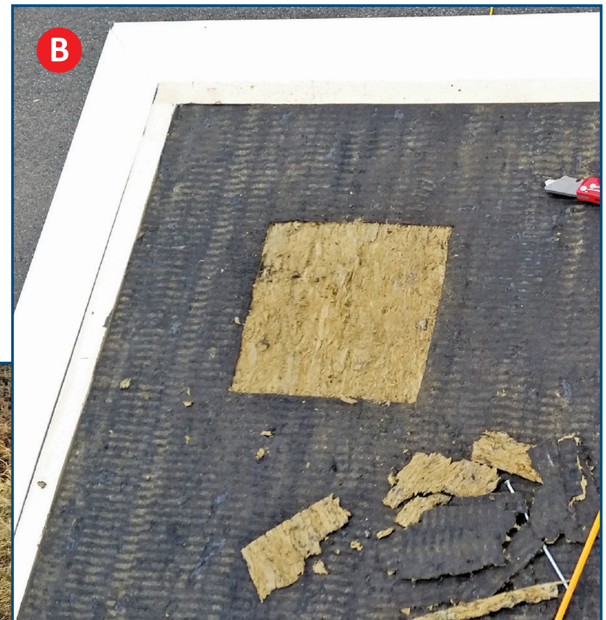


Figure 3 – Roof Panel 1 RH and temperature sensors being installed on first layer of insulation. Wetting system not yet installed.

Figure 5 – Roof 1 vapour diffusion port construction steps, showing A) an air barrier membrane installed on open top of vapour diffusion apparatus and taped to the sides, B) black asphalt facer being removed from the roof insulation at the vapour diffusion port location, and C) vapour diffusion port on finished roof assembly.



Each roof assembly received a number of temperature, RH, and moisture-content sensors that were all wired to a data logging system to continuously monitor the conditions inside the roof assemblies. The schematic locations of these sensors are shown in *Figure 1*. The red ovals (solid and dashed) indicate specific sensors used during analysis and will be further explained in the data analysis section.

Moisture-content wafer sensors of a known wood species were installed within each roofing assembly. Typically, in moisture-monitoring projects, metal pins are installed in wood construction materials (i.e., framing and sheathing) to measure the moisture content of the material; but in assemblies without wood materials, the pins are installed in a small wood wafer that experiences changes in moisture content with changes in RH of the surrounding environment. Wood moisture content can be determined from electrical resistance of wood based on the Garrahan equation (Garrahan, 1988; Onysko et al., 2010). The wood moisture-content wafers were installed in combination with a temperature sensor to correct the moisture-content readings for temperature effects.

RH sensors were installed at various locations within each roofing assembly as well. The RH sensor was always installed in combination with a temperature sensor, both of which were protected by a vapour-permeable, water-resistant cover.

Figure 3 and *Figure 4* show the standard combination of RH, moisture content, and temperature sensors installed in the roof panels as described in *Figure 1*. A plastic tube was installed to the centre of the wetting storage media from the interior of the test hut to enable a controlled amount of water to be injected to a controlled location (shown in *Figure 2*).

One of the greatest advantages to using a test hut for analysis, compared to instrumenting roofs in existing buildings in operation, is that the research in test huts can easily stress the roofs with high moisture, typically in the form of liquid water. In most cases, building owners are not interested in injecting water into the roofs being monitored on operating buildings. It is often difficult to determine the performance of an enclosure system without stressing the moisture tolerances to determine the comparative risk or performance of certain construction techniques. In this specific research, one of the objectives was to determine performance following the addition of water.

Roof Panel 1 was constructed with an exterior vapour diffusion port as seen in the *Figure 1* schematic and the *Figure 5C* photo. The intent of the vapour diffusion port is to allow moisture that becomes trapped within the roofing insulation to dry outward via vapour diffusion (since the stone wool insulation is vapour-permeable). The vapour diffusion port is a sheet metal box with an open top and bottom and a flange on the bottom that is integrated between the two layers of the roof membrane. A vapour-permeable air barrier sheathing membrane (approximately 9000 ng/Pa·s·m^2 [160 perms]) was installed over the vapour diffusion port and taped to the sides before the cap was installed (*Figure 5A*), ensuring no air circulation between the exterior environment and interior of the vapour diffusion port and the insulation material.

TABLE 1 - ROOF WETTING EVENTS		
Wetting Event	**Start Date**	**Total Volume Injected**
1	June 6, 2016	75 mL (2.5 fl. oz.) 2x/day, 5 days – Total of 750 mL (25 fl. oz.)
2	October 17, 2016	75 mL (2.5 fl. oz.) 2x/day, 5 days – Total of 750 mL (25 fl. oz.)
3	June 26, 2017	150 mL (5 fl. oz.) 2x/day, 5 days – Total of 1500 mL (1.5 L) (51 fl. oz.)

Table 2 – Roof wetting events.

ENCLOSURE WETTING SYSTEMS

The wetting system consists of a water storage medium with a tube ending in the middle, allowing water injection from the interior of the test hut, so that a controlled amount of water can be injected to the middle of the water storage material. The wetting system was installed between the two layers of insulation. A photograph of the installed wetting system is shown in *Figure 2* prior to adding the top layer of insulation. A wetting event consisted of injecting water twice a day for five days. There were three wetting events during the research program (*Table 2*).

CLIMATE MONITORING

Two steel masts on the roof of the test facility support a weather station at a height of 18 ft. (5.5 m) above ground level. The monitoring system continuously collects weather data, including temperature, RH, wind speed and direction, precipitation, and solar energy.

MONITORING SYSTEM DATA ANALYSIS

Normal Operating Conditions

The first comparison analysis was conducted prior to the intentional wetting events. The roofs were constructed in the fall of 2015, and the insulation was protected from rain during construction. Even though there was no liquid water entering the roofing assemblies during construction, the ambient RH is high in the fall, and water vapour will adsorb to all hygroscopic materials prior to finishing the roof membrane.

Figure 6 shows the measured moisture content at the wood wafer between the insulation layers at Location C prior to the first intentional wetting event. This monitoring location is directly below the vapour diffusion port in Roof Panel 1 (as indicated by the solid red oval in *Figure 1*). During the winter months, all of the moisture-content readings are quite low until approximately the end of February 2016. In March, there is significantly more fluctuation in the measured moisture content, with Roof Panel 1 having the highest peaks, and Roof Panels 2 and 3 being lower. It is probable that the high springtime exterior RH may have been entering the roofing assembly through the vapour diffusion port, resulting in measured peaks in the moisture content between the layers directly below the vapour diffusion port.

In mid April 2016 (vertical black dashed line in *Figure 6* and *Figure 7*), when exterior temperatures were consistently warmer, the measured moisture content of the wood wafers in Roof Panels 1 and 2 increased and the measured moisture content in Roof Panel 3 with the smart vapour barrier decreased. The measured moisture content between the insulation at Location C was lower in Roof

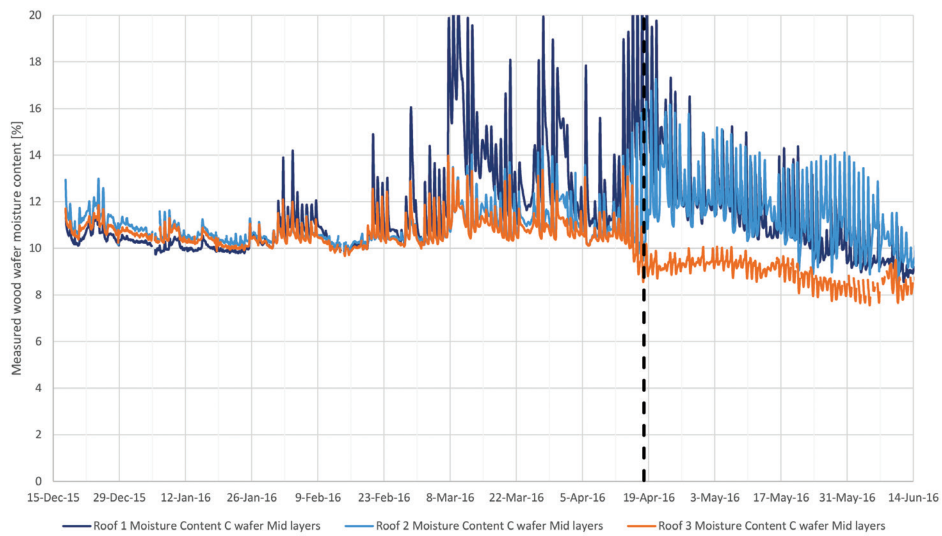


Figure 6 – Measured moisture content at Location C between the roofing insulation in all three roof assemblies, under normal operating conditions, Dec. 15, 2015 to June 14, 2016.

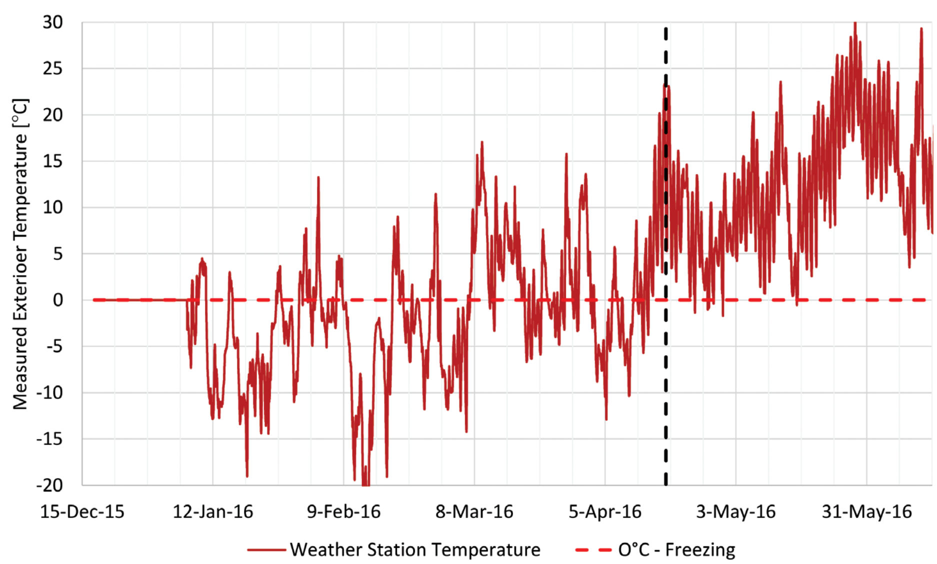


Figure 7 – Measured exterior temperature showing seasonal temperature increase in April 2016.

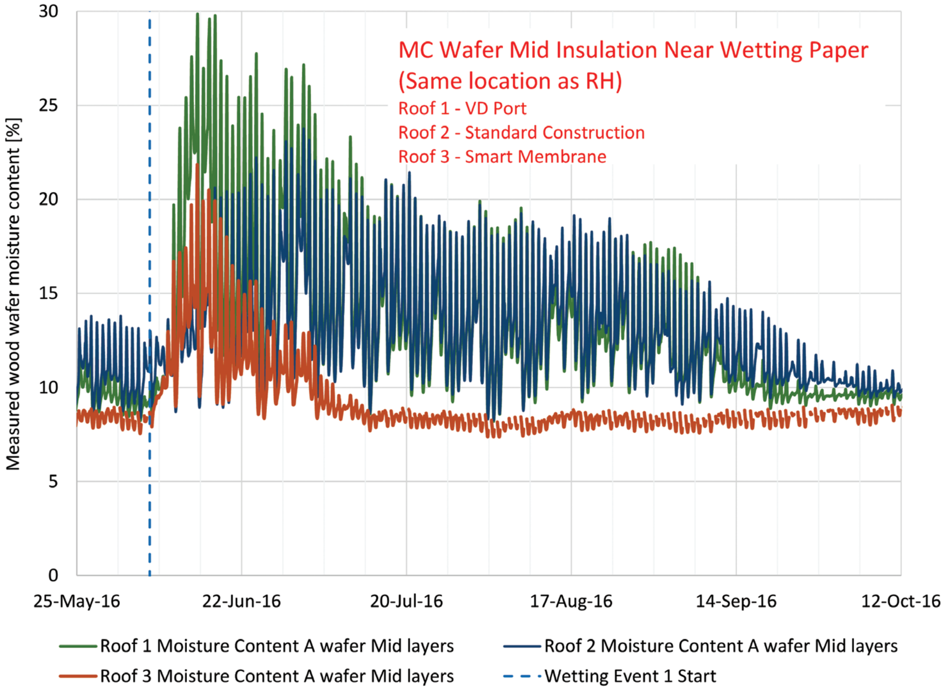


Figure 8 – Measured moisture content at Location A between the roofing insulation in all three roof assemblies. Wetting Event 1, drying period June 21 to Oct 16, 2016.

3 until mid June, when the first intentional wetting event was conducted (first wetting event not shown on *Figure 6*). Similar results were also measured at the same location with the RH sensor. The measured RH at Location A in Roof Panel 3 decreased noticeably compared to Roof Panels 1 and 2 in mid April, following the rise in average daily springtime temperatures.

The measured moisture content and RH data show that there is a measured improvement in the amount of moisture in Roof Panel 3 with the vapour-open air control layer even though no liquid water was present and all of the roofs started at the same "dry" moisture conditions.

Controlled Wetting Event 1 – June 6, 2016

Water injections commenced on the morning of June 6, 2016. A total of 750 mL (25 fl. oz.) of water was injected over five days: 75 mL (2.5 fl. oz.) twice a day (once in the morning and once in the afternoon). This water was injected through a plastic tube to the centre of the water storage media in the location shown in *Figure 1*.

Figure 8 shows the measured moisture content of a wood wafer for all three roof assemblies at Location A (dashed red oval on *Figure 1*), approximately 18 in. (457 mm) from the middle of the wetting system between the layers of insulation. It is clear from the graph that the moisture-content wafer in Roof Panel 3, with a smart vapour retarder air barrier, dried in approximately three to four weeks. Roof Panels 1 and 2 begin to show slow drying over the course of 17 weeks following the intentional wetting event. Roof Panel 1 with the vapour diffusion vent does not show substantially better drying than Roof Panel 2.

The measured RH following the first wetting event in all three roof panels at Location A below the insulation (between the insulation and air control layer) is shown in *Figure 9*. Roof Panels 1 and 2 are showing measured RH at 100% that occasionally falls below 70% in the first 13 weeks following the wetting event. Roof Panel 3, constructed with the smart vapour retarder air barrier, has a much lower measured RH: between 30% and 90% at three to four weeks following the initial wetting event, indicating that water in the assembly is drying to the interior from Roof Panel 3.

The measured RH at Location A between the two layers of 3-in. stone wool insulation had similar results to the measured moisture content following the first wetting event. The measured RH three to four weeks after the initial wetting event in Roof Panel 3 is significantly lower than Roof Panels 1 and 2. Results for Roof Panel 3 with a smart vapour retarder indicate an ability to dry to the interior. The slow decrease in RH in Roof Panels 1 and 2 (up to 13 weeks after the initial wetting event and slightly faster decrease up to 13 weeks after the initial wetting event) indicates cooler exterior temperatures and a greater moisture movement and accumulation towards the upper roof membrane. There is no substantial difference in drying of the moisture in the roof assembly between Roof Panel 1 with the vapour diffusion port and Roof Panel 2 without.

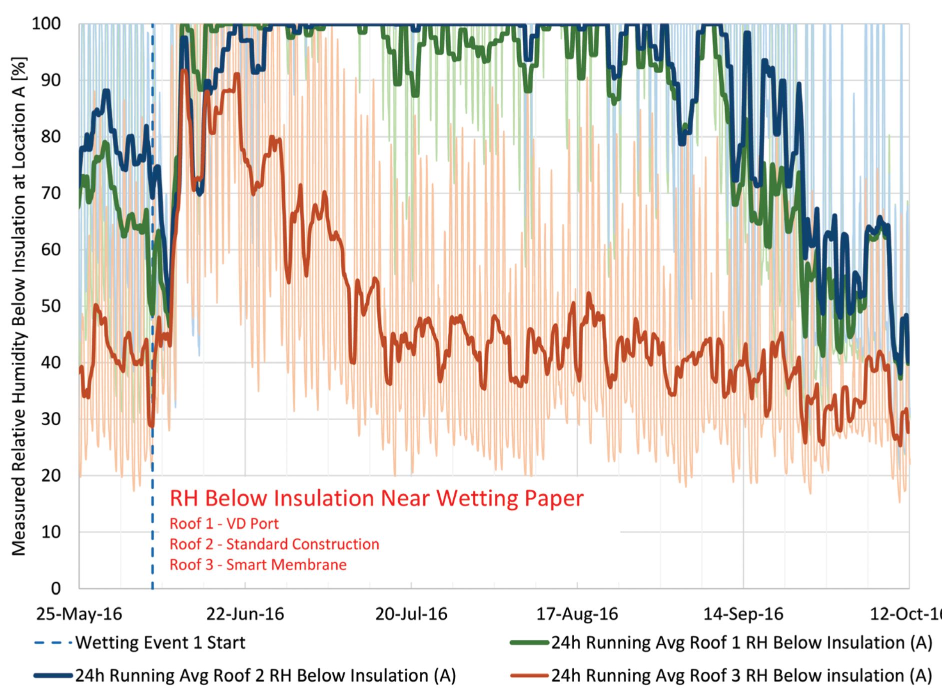


Figure 9 – Measured RH at Location A below the roofing insulation in all roof panels. Wetting Event 1, drying period June 21 to Oct 16, 2016.

Controlled Wetting Event 2 – October 17, 2016

Water injections commenced on the morning of October 17, 2016. A total of 750 mL (25 fl. oz.) of water was injected over five days: 75 mL (2.5 fl. oz.) twice a day (once in the morning and once in the afternoon), similarly to the first controlled wetting event.

Figure 10 shows the measured moisture content of a wood moisture-content wafer for all three roof panels at monitoring Location A (dashed red oval on *Figure 1*), approximately 18 in. (457 mm) from the middle of the wetting system. On approximately November 19, 2016, about one month following the wetting, the exterior temperature fell below freezing and was mostly below freezing until February 19, 2017, as shown by the black temperature line in *Figure 10*. The decrease in exterior temperature correlates to a decrease in the measured moisture content for the winter months. During the very cold period, any time the ambient temperature exceeded freezing, there was a peak in the measured moisture content that correlated. We hypothesize that this is because all of the moisture in the roof assembly froze and accumulated at the top surface of the insulation at the roofing membrane as a result of the vapour pressure gradient within the roofing insulation and was not available in liquid form to be measured by the moisture-monitoring system.

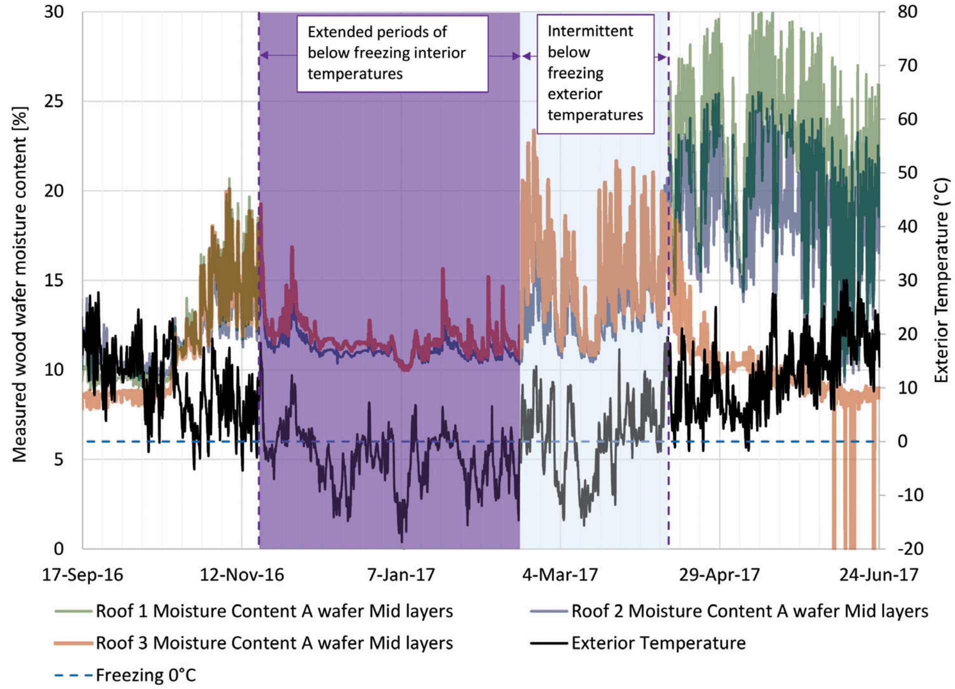


Figure 10 – Exterior temperature and measured moisture content at Location A in all three roof panels following the second intentional wetting event. Outdoor temperatures below freezing mid-November to mid-March.

From February 18 to mid April, 2017, the temperature fluctuated between freezing and thawing (black line on *Figure 10*), and all three roof panels showed essentially the same measured wood wafer moisture content. On approximately April 9, 2017, the temperature was consistently warm enough that all of the water became liquid and was redistributed through the roof insulation. Roof Panels 1 and 2 experienced elevated moisture contents as the water was redistributed throughout the insulation, increasing to a maximum of 25-30% on a daily cycle. Roof 3 immediately showed drying once the liquid water and warmer temperatures occurred, allowing diffusion through to the interior.

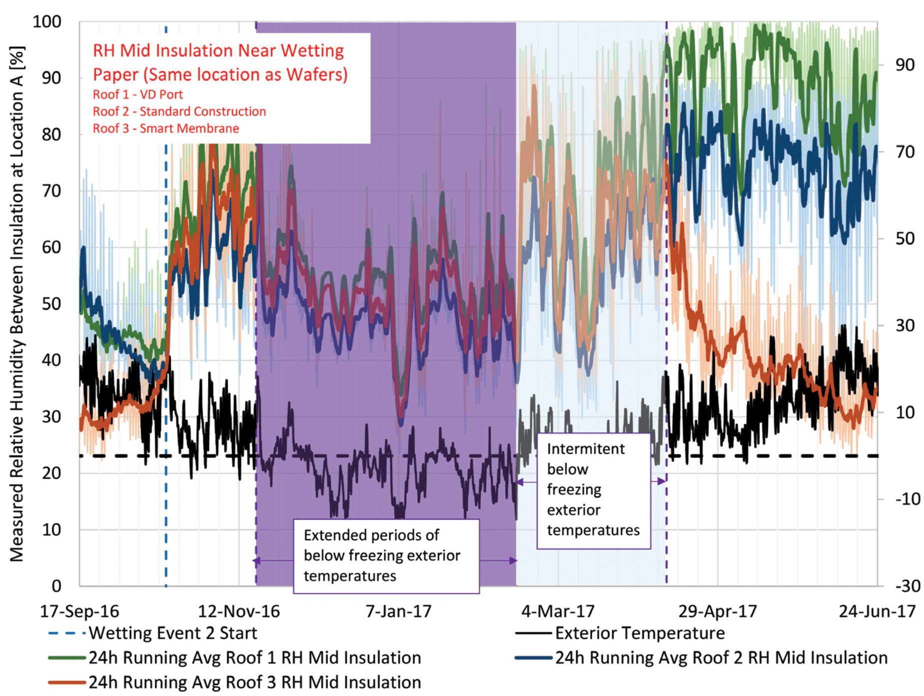


Figure 11 – Measured RH at Location A between the insulation layers in all roof panels, following Wetting Event 2, drying period Oct 17, 2016 to June 25, 2017.

Similarly to the moisture-content data in *Figure 10*, the RH below the insulation (between the insulation and the air control layer) at Location A showed a decrease and relatively constant low values (30-45%) from approximately November 19, 2016, through February 17, 2017, corresponding to long-term freezing temperatures. After the freezing and intermittent freezing conditions, Roof Panels 1 and 2 showed measured RH at 100% that occasionally fell below 80% at Location A beneath the insulation. No drying occurred on Roof Panels 1 or 2. RH beneath the insulation on Roof Panel 3 generally decreased following the intermittent freezing period and was lower than Roof Panels 1 and 2, although it still showed considerable fluctuations and did not reach 100%.

Figure 11 shows the measured RH between the two layers of 3-in. stone wool roofing insulation at Location A (dashed red oval on *Figure 1*) approximately 18 in. (457 mm) from the site of water injection for Wetting Event 2. RH between the insulation in Roof Panel 1 decreased after the freezing and intermittent freezing periods to mostly between 30 and 50%. RH in Roof Panels 1 and 2 mostly remained above 70% and occasionally less. There was no definitive drying in Roof Panel 1 or 2, and no indication that the vapour diffusion port in Roof Panel 1 was assisting with drying compared to Roof Panel 2. The measured RH between the layers of insulation in Roof Panel 3 dried relatively quickly once the springtime temperatures were consistently above freezing, starting in mid-April.

The analysis from Wetting Event 2 shows that once the moisture in the roof assembly thawed and there was energy available (warmer exterior temperatures and solar energy) in the spring, Roof Panel 3 showed measured drying of the moisture within the assembly, both by measured RH and by measured moisture content.

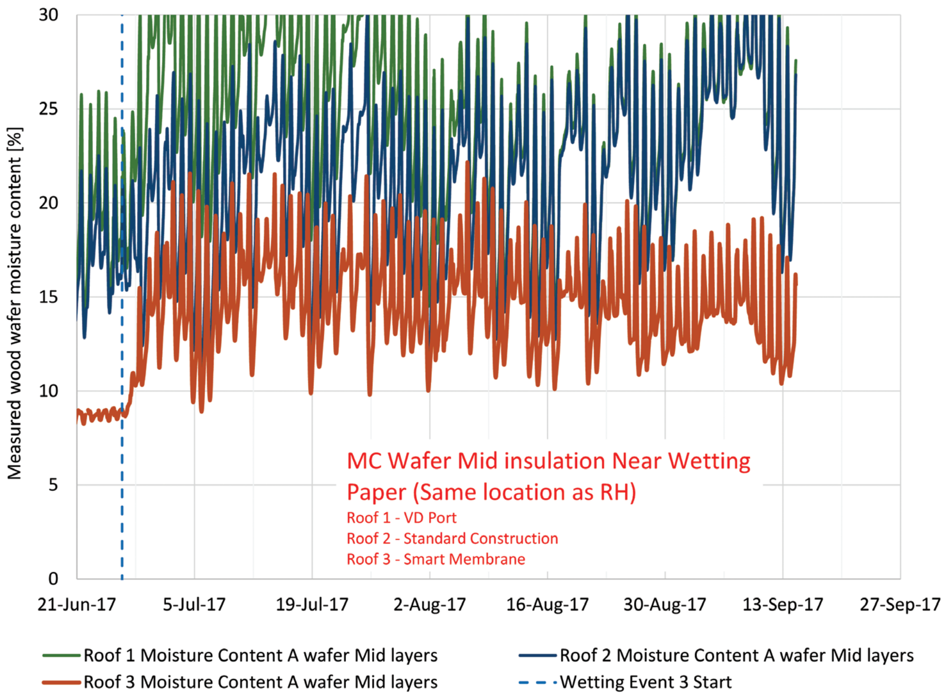


Figure 12 – Measured moisture content at Location A in all three roof assemblies following the third intentional wetting event, drying period June 26 to Aug 30, 2017.

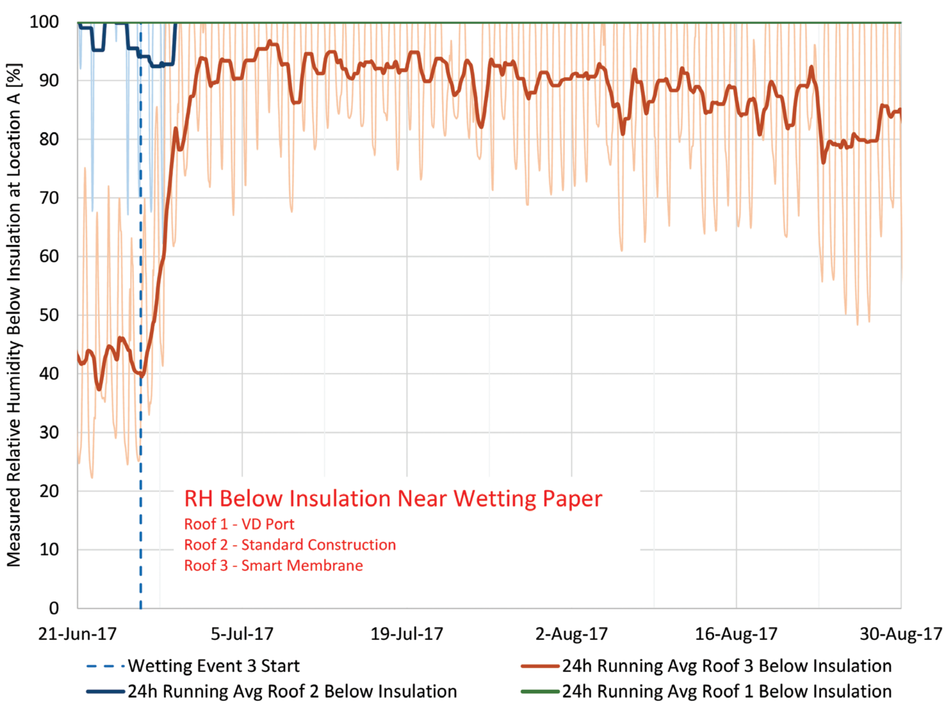


Figure 13 – Measured RH at Location A below the roofing insulation in all three roof assemblies following the third intentional wetting event, drying period June 26 to Aug 30, 2017.

Controlled Wetting Event 3 – June 26, 2016

During the first two wetting events, Roof Panel 3 was able to dry the amount of water added much more quickly and efficiently than Roof Panels 1 and 2. For the third wetting event, near the end of the experimental program, it was decided to stress the roof assembly even more with a larger wetting dose.

Water injections commenced on the morning of June 26, 2017. A total of 1500 mL (51 fl. oz.) of water was injected over five days: 150 mL (5.1 fl. oz.) twice a day, once in the morning and once in the afternoon. The third wetting event was double the volume of the first two wetting events. This water was injected through a plastic tube to the centre of the water storage media in the location shown in *Figure 1*.

Figure 12 shows the measured moisture-content for all three roof assemblies at Location A (dashed red oval on *Figure 1*), approximately 18 in. (457 mm) from the middle of the wetting system. It should be noted that Roof Panels 1 and 2 start at a higher moisture-content reading than Roof Panel 3. Even though the measured moisture content in Roof Panel 3 is lower than Roof Panels 1 and 2 following the wetting event (and generally below the 20% moisture-content threshold of concern), there does not appear to be a drying trend to the data for Roof Panel 3 over the monitoring period. Roof Panel 1 initially has the highest measured moisture content, but after a few weeks of moisture redistribution, the readings for Roof Panels 1 and 2 are nearly identical.

The measured RH in all three roofing assemblies at Location A below the insulation is shown in *Figure 13* for Wetting Event 3. Roof Panels 1 and 2 show measured RH at 100% for the entire monitoring period. Roof Panel 3 had substantially dried from Wetting Event 2, and starts at a lower moisture level after Wetting Event 3. The RH for

Roof Panel 3 fluctuates between 100% and approximately 80% initially but does show a drying trend with a gradually decreasing average RH. This indicates the start of drying to the interior in Roof Panel 3 at five weeks, albeit at a slower rate than after the previous two wettings, which had half the wetting volume.

Figure 14 shows the measured RH between the two layers of 3-in. stone wool roofing insulation at Location A (dashed red oval on Figure 1) approximately 18 in. (457 mm) from the site of water injection. Prior to the wetting event, Roof Panels 1 and 2 were at approximately 75% and 85% RH, respectively, while Roof Panel 3 had more substantially dried to 35%. Following the wetting, Roof 3 had the lowest measured RH but did not appear to exhibit a drying trend through the monitoring period. Roof Panels 1 and 2 had higher measured RH levels following the wetting—between 80% and 100%—and also did not exhibit any drying trends.

Further analysis was conducted at Location B in the roof assemblies (40 in. [1 m] from the wetting system), to compare the performance of the three roofs following Wetting Event 3. *Figure 15* shows that at Location B for Roof Panel 3 (with the smart vapour control layer), the measured RH running average is much lower than for either Roof Panel 1 or 2.

Similarly, in the measured moisture-content analysis at Location B, Roof Panel 3 had the lowest measured moisture content with less measurement fluctuation following the addition of water for Wetting Event 3.

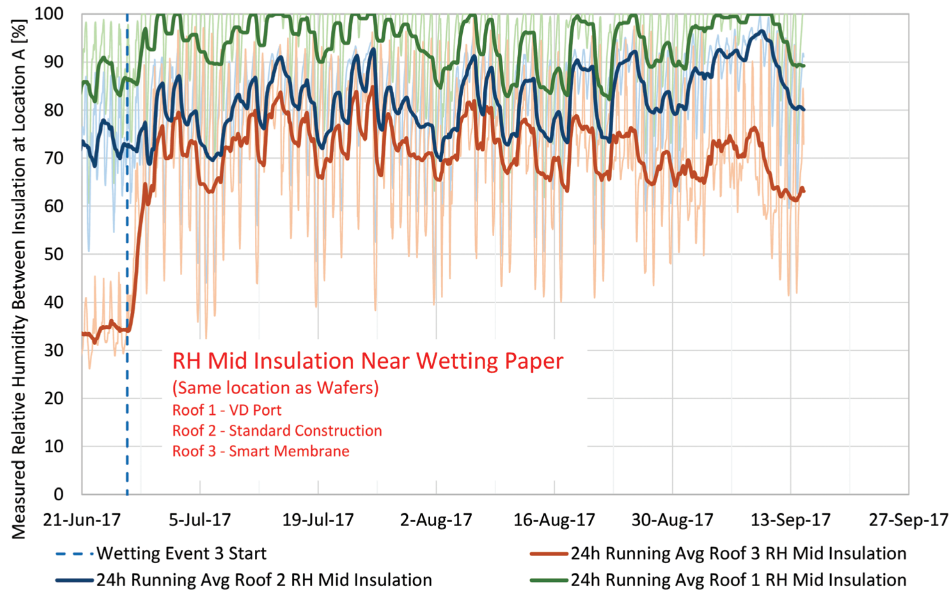


Figure 14 – Measured RH at Location A between the insulation layers in all three roof assemblies following the third intentional wetting event, drying period June 26 to Aug 30, 2017.

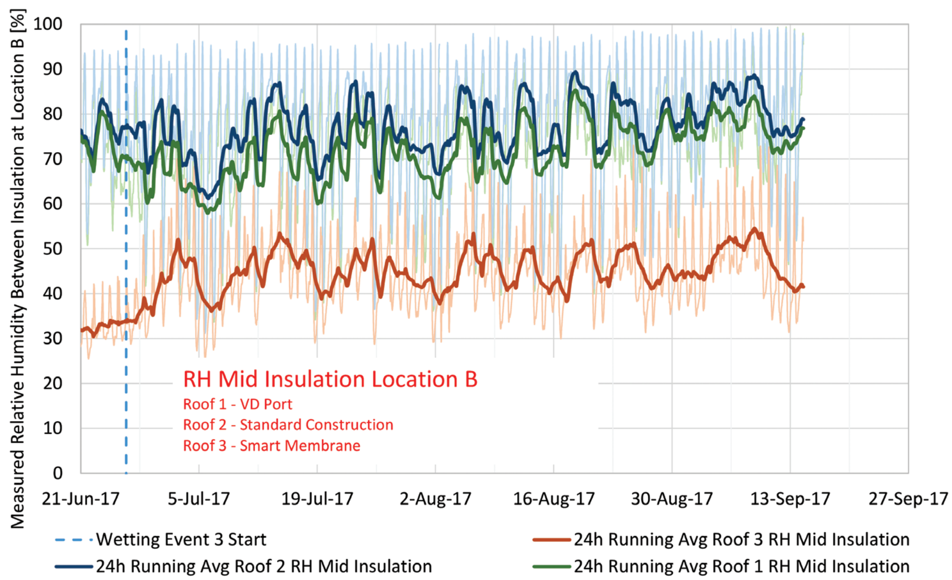


Figure 15 – Measured RH at Location B between the insulation layers in all three roof assemblies following the third intentional wetting event, drying period June 26 to Aug 30, 2017.

CONCLUSIONS

Under normal operating conditions (i.e., with no leaks), the analysis showed that a standard roofing assembly worked well. However, the roof with a smart vapour barrier allowed some moisture diffusion into the interior space, resulting in a drier assembly following the first winter.

Following the injection of 750 mL (25 fl. oz.) of water to simulate a small localized rain leak, the analysis showed that a roof assembly with a smart vapour retarder installed over the metal deck allowed the water to mostly dry within five weeks of wetting. Roof Panel 1, with traditional construction (a vapour barrier installed on the roof deck) and vapour diffusion venting ports, showed slow drying over 18 weeks. There was no indication from the data that the vapour diffusion port installed increased the drying rate of the assembly compared to standard construction.

Following the third wetting event of 1.5 L (51 fl. oz.)—double the amount of each of the first two wetting events—the roof with a smart vapour barrier had lower measured moisture levels, but did not demonstrate a significantly improved drying rate at Location A (18 in. [457 mm] from the wetting system) in the nine weeks following the wetting event. It is likely that if the monitoring had continued further, we would have seen an eventual decrease in the amount of water at Location A. Following the third wetting event, analysis at Location B in the roof assemblies (40 in. [1 m] from the wetting system) showed significantly lower measured moisture content and RH in the roof with the smart retarder, as compared to the roof with a vapour barrier and vapour diffusion port.

Installation of the smart vapour retarder over the metal deck instead of a vapour-impermeable membrane demonstrated measurable improvement of drying ability. This enhanced drying could improve

Roof Panel	Structure	Air/Vapour Control	Thermal Control	Water Control Membrane
1	Metal roofing deck	Self-adhered vapour-permeable membrane 11-17 perms (630 - 970 ng/Pa·s·m^2)	2 layers of 3-in. stone wool	2-ply mod-bit roofing
2	Metal roofing deck	Self-adhered vapour-permeable membrane 11-17 perms (630 - 970 ng/Pa·s·m^2)	2 layers of 3-in. roofing polyisocyanurate	2-ply mod-bit roofing
3	Wood deck (OSB)	Self-adhered vapour-permeable membrane 11-17 perms (630 - 970 ng/Pa·s·m^2)	2 layers of 3-in. stone wool	2-ply mod-bit roofing

Table 3 – Roofing study experimental construction variables.

long-term durability and avoid moisture-related issues within the roofing assembly. The diffusion vent port design did little or nothing to improve performance in this field exposure test.

FURTHER TESTING

As with most research, results often lead to more questions. Some of the questions resulting from this research include:

1. Would the self-drying roof (Roof Panel 3) work equally well with polyisocyanurate roofing insulation instead of stone wool insulation?
2. There was significant improvement with the smart vapour barrier, but what range in vapour permeance is required, and are there material options more suitable for construction sites, compared to the loose-laid, sheet-applied plastic over the metal deck used in this research program?

Based on these questions about constructability and vapour permeance, as well as interest in applications to residential low-slope roofing, a second round of full-scale roof testing is currently underway. The experimental plan for the second round is similar to the first round, with intentional wetting events in different seasons, and will continue for a minimum of at least one year, capturing all four seasons. The main experimental variables of the current round of testing are shown in *Table 3*, and the research findings will be available in the future.

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