Asphalt Shingle Sloped Roofing Research Study

Phase 1

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Executive Summary

Moisture problems in sloped wood-frame attic roof assemblies are often attributed to rain water ingress, inadequate ventilation of the attic space, and air leakage condensation from interior spaces or ductwork. However, detailed investigation and testing of many of these attics has found that these factors cannot wholly account for the observed problems. Wetting from other sources, including condensation of outdoor attic ventilation air caused by night sky cooling, and in some cases rainwater ingress through asphalt shingles, is hypothesized as additional factors. These roofs are generally constructed to meet current building code and third-party roofing warranty requirements.

These roofing problems are proving to be a significant burden on homeowners and warranty insurers. Warranty claims are often filed for moisture ingress and mould issues within attics, and mould in attics can significantly impact property values. Additionally, repairing moisture damage within attics is costly and a significant inconvenience to property owners and the warranty provider. Furthermore, the success of many of these repair efforts has been poor, with mould growth recurring a few years after a full remediation and air sealing work has taken place. This suggests the presence of other underlying wetting mechanisms.

In an effort to further understand the cause of attic moisture problems and develop potential remediation solutions, a field exposure monitoring study was undertaken in Vancouver, BC. The study investigated sheathing moisture absorption caused by night sky cooling and ventilation air condensation as well as the impact of shingle underlayment types on potential exterior moisture sources. The study included both a controlled field exposure study to measure the moisture contents, temperatures, condensation, and mould growth on several roof huts as well as supplemental laboratory testing. The primary objective of this study was to conclusively demonstrate that sloped wood-frame attic roofs constructed according to best practice guidelines experience moisture-related problems even in the absence of interior moisture sources and with unrestricted ventilation. The secondary objective was to assess the efficacy of various wood surface treatments at preventing mould growth on the roof sheathing.

The results from this study indicate that roofs constructed to best practice guidelines are subject to night-sky cooling causing condensation of ventilation air on the underside of the sheathing. Underlayment permeability did not appreciably affect the moisture contents of the sheathing. Surface mould growth was also observed on all roof pitches on both North and South elevations, with the South elevation exhibiting a lesser degree of mould growth. Nominal exterior insulation (approximately R-1), by way of venting, did not noticeably decrease the occurrence of condensation.

Some biocidal treatments proved relatively effective in inhibiting mould initiation; however, many others provided no benefit and in some cases, worsened the mould growth compared to untreated wood. Follow-up field testing and additional work by FPInnovations was undertaken to further assess the efficacy of wood surface treatment products.

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1 Introduction

Moisture problems in sloped wood-frame attic roof assemblies are common and typically manifest as the degradation of the roof sheathing and fungal growth. Often this type of damage is attributed to rain water ingress through the roof assembly, inadequate ventilation of the attic space, and condensation associated with air leakage from the interior spaces or ductwork or with the re-entrainment of humid exhaust air into the vented space. Figure 1.1 to Figure 1.4 provide images of typical fungal growth and damage found in sloped wood-frame attic roof assemblies.

Figure 1.1 Visibly wet roof sheathing caused by rainwater ingress through the shingles and underlay

Figure 1.2 Locally stained and wet sheathing due to condensation (frost) of humid air which is leaking from a poorly sealed bathroom exhaust duct

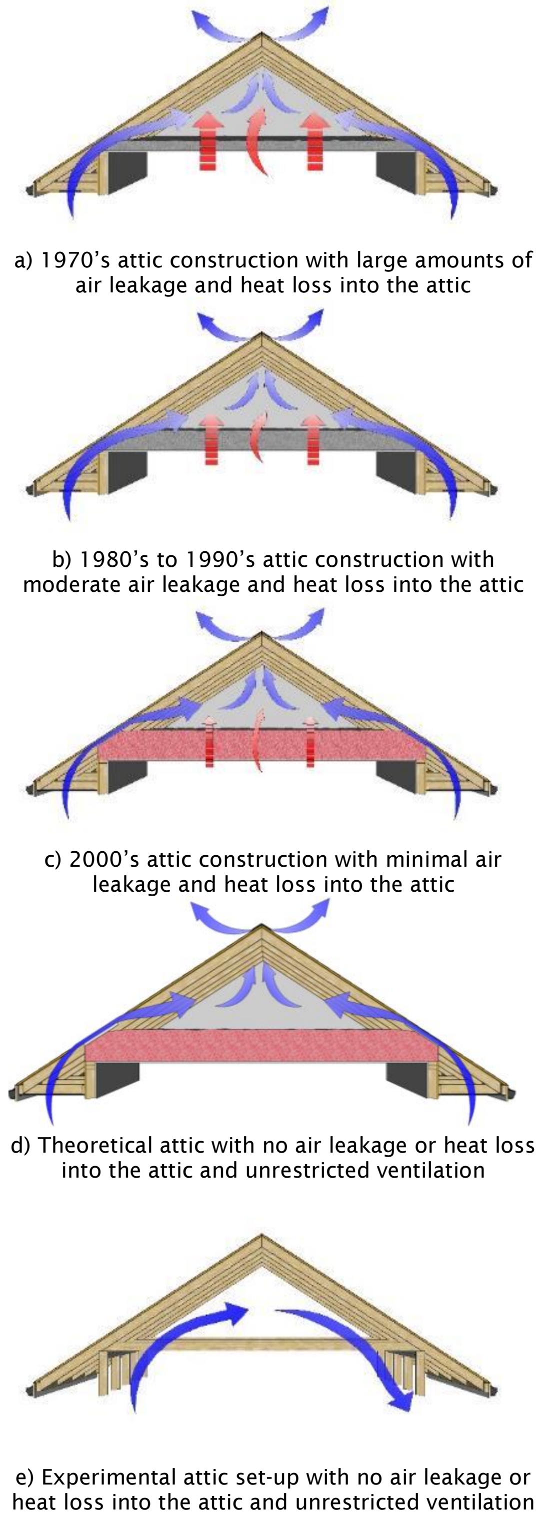
Figure 1.3 Widespread stained, wet, and deteriorated sheathing within wood-frame attic from persistent indoor and exhaust duct air leakage and poor attic ventilation

Figure 1.4 Fungal growth on sheathing within the ventilation baffles as a result of the entrainment of humid, outdoor air

These problems are similar to problems observed in the past in similar marine/temperate climate zones in Sweden (Arfvidsson and Harderup, 2005; Hagentoft and Kalasgasidis, 2010). In many cases this fungal growth does not lead to structural damage of the sheathing or necessarily create health problems (ACOEM, 2003; Lstiburek et al, 2008), but it is nonetheless perceived to be a possible health risk to the occupants or a property value risk to the owners.

In recent years, a trend towards highly insulated attics has been pursued and seemingly correlates with increased observations of moisture problems in wood-frame attics, particularly in the Lower Mainland of BC (Climate Zone 4C, temperature marine) (Dell et al. 2011, Roppel et al. 2013). Improvements in attic construction have typically led to a decrease in the leakage of interior air into attics due to improved ceiling airtightness, and consequently a decrease of the attic moisture load as illustrated in Figure 1.5. Concurrently, attics were also constructed with more insulation (i.e. R-40+) to reduce building energy consumption which has reduced the heat gain into attics, and, as a side effect, has reduced the drying capacity of the roof sheathing. As more insulation is added to these attics, air leakage from the interior is reduced, and ventilation is improved, these attics approach a state of functioning completely independently from the building on which they are constructed, as is shown schematically in Figure 1.5 d). This decoupling effect can have both positive and negative implications for the performance of the roof sheathing and on the risk for wetting and associated damage.

Detailed investigations and testing of many of these attics have shown that the traditional wetting mechanisms identified above cannot account for the observed fungal growth as moisture related problems have been found to occur in the absence of rainwater ingress and despite relatively airtight ceilings and adequate ventilation (i.e. constructed to meet current building code and RCABC roofing requirements or better). Consequently, it is hypothesized that in these cases other mechanisms are affecting the moisture performance of these roof assemblies, and specifically of the attic sheathing.



a) 1970's attic construction with large amounts of air leakage and heat loss into the attic

b) 1980's to 1990's attic construction with moderate air leakage and heat loss into the attic

c) 2000's attic construction with minimal air leakage and heat loss into the attic

d) Theoretical attic with no air leakage or heat loss into the attic and unrestricted ventilation

e) Experimental attic set-up with no air leakage or heat loss into the attic and unrestricted ventilation

Figure 1.5 – Schematics showing historical ventilation, insulation, and air leakage arrangements for attics (a, b, & c) and for a theoretical attic (d). Blue lines show ventilation airflow into and out of the attics, red dashed lines and curved lines respectively represent heat loss and air leakage into the attics from the interior.

Phenomena that may previously have been masked by excessive heat loss in older, poorly insulated and air-leaky attics can become apparent in modern well-insulated and airtight attics. In addition, changes to plywood roof sheathing material properties over the past few decades (e.g., species and relative levels of heartwood and sapwood from later-growth timber) may also be contributing to the current issues. When the traditional damage mechanisms are eliminated, it is hypothesized that there are two remaining potential sources: attic ventilation air condensing on the underside of the sheathing due to night sky cooling and inward vapour diffusion.

The hypothesized condensation due to night sky cooling would occur when the roof sheathing temperature falls below the dew point temperature of the outdoor air because of radiation to the night sky. This causes condensation (and potentially frost) on the underside of the sheathing which is absorbed and increases the sheathing moisture content. Sufficiently elevated sheathing moisture contents may create conditions which support fungal growth. This wetting mechanism may previously have been masked by excessive heat loss in older, poorly insulated and air-leaky attics and has now become apparent in modern well-insulated and airtight attics.

The hypothesized inward vapour diffusion wetting mechanism is a process by which precipitation and surface condensation is absorbed by the shingles or collected in gaps between the shingles and driven into the roof assembly as vapour when subjected to elevated temperatures (i.e. solar heating). In addition, changes to plywood roof sheathing material properties over the past few decades (e.g., species and relative levels of heartwood and sapwood from later-growth timber) may also be contributing to the current moisture issues.

In an effort to further understand the cause of the observed moisture related problems in attics and to develop industry accepted solutions, a research study was undertaken to investigate the potential moisture sources and methods for mitigation of fungal growth and prevention of degradation. This research consists of both a controlled field exposure study and supplemental laboratory testing.

1.1 Objectives

The primary objective of this study was to conclusively demonstrate that sloped wood-frame attic roof assemblies experience wetting in the Lower Mainland of BC which can result in fungal growth and degradation despite the elimination of typical moisture sources, and that this cannot be prevented by ventilation alone. Once this was established, this study worked to identify and evaluate the critical wetting mechanism(s) and to assess potential mitigation strategies including:

→ The addition of a vented layer between the shingles and the roof underlayment in an effort to disconnect the sheathing from the night sky cooling effects experienced by the shingles, and

→ The application of various wood treatment products to the sheathing to prevent fungal growth and sheathing degradation.

This study focused on only these two mitigation options; however, parallel work is being conducted by FPInnovations, BC Housing, Morrison Hershfield, and the British Columbia Institute of Technology (BCIT) to investigate additional strategies. Alternative roof configurations including unvented attics or exterior insulated roofs, while viable alternatives to traditional ventilated attics, were not evaluated as part of this study.

1.2 Methodology & Scope

To address the study objectives, the research study employed both a field monitoring program and supplementary laboratory testing. The methodology for each of these components of the study is described in this section.

The field monitoring program was divided into two parts. The first part consisted of evaluating standard attic roof construction and the efficacy of wood treatments at preventing fungal growth and degradation. For the second part, the control roof was modified to include a ventilation layer between the shingles and the roof underlay. The other three test roofs were not modified for the second part, with the exception of the installation of additional sensors. The first part of the study was from September 2012 to October 2013, and the second part was from November 2013 until April 2014. Four wood treatments were applied in October 2012, and two additional treatments were applied in April 2013.

1.2.1 Roof Hut Arrangements

To assess the field performance of wood-frame attic roof assemblies, four roof huts were constructed, each 6 feet wide by 6 feet long in plan dimension. The roof huts were constructed using ½” plywood sheathing, 2x4 wood framing, and dark coloured three-tab shingles as shown in Figure 1.6 to Figure 1.10. Three of the roofs were constructed at 3:12, 4:12, and 6:12 slopes respectively with standard BC Building Code minimum asphalt impregnated #15 roofing paper underlay, while the fourth “control” roof was constructed at a 3:12 slope using an impermeable self-adhered membrane (SAM) underlay.

a) 3:12 Slope roof with roofing felt underlay

b) 4:12 Slope roof with roofing felt underlay

c) 6:12 Slope roof with roofing felt underlay

d) 3:12 Control roof with SAM underlay

Figure 1.6 – Schematics of field monitoring roof huts

Figure 1.7 – Roof huts under construction with plywood sheathing installed

Figure 1.8 – #15 roofing felt underlay and perimeter flashings installed

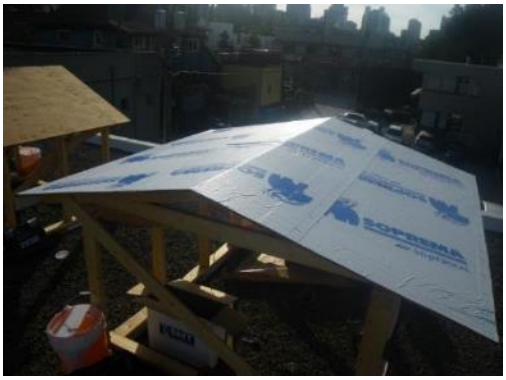


Figure 1.9 – Self-adhered membrane (SAM) underlay installed at control 3:12 roof

Figure 1.10 – Three-tab asphalt shingles being installed by roofing contractor

The four roof huts were placed on the open low-slope roof of a two-storey commercial building in Vancouver, BC (the RDH office building) in order to expose them to exterior conditions while also decoupling them from the potential impact of a heated attic, indoor air-leakage, duct leakage, and restricted ventilation. Additionally, the installation of the self-adhered vapour-impermeable membrane on the "control" roof was intended to eliminate the potential for all wetting of the sheathing from the topside of the roofs including by rainwater ingress and by inward vapour diffusion. This controlled roof hut approach allows for the evaluation of the field performance of these assemblies under unrestricted ventilation conditions while eliminating many of the conventional wetting mechanisms, and is representative of well-ventilated attic roofs, soffits, or overhangs. The roof huts were constructed in late August 2012 and were roofed by mid-September 2012 under seasonally dry conditions.

The roof huts were arranged such that one side of the roof slope faces due North and one side faces South to investigate the impact of solar radiation on performance. The different orientations influence how the roof heats up and dries, and potentially how well the self-sealing stripping of the shingles engages. The arrangement of the roof huts is shown in Figure 1.11 and Figure 1.12.

Figure 1.11 – Completed roof huts in-place on low-slope commercial roof-top. Black three-tab shingles installed on test roofs, dark grey shingles from same manufacturer installed on control roof with SAM underlay

Figure 1.12 – Exposure of roof huts on top of 2 storey commercial building roof-top. From left to right: 3:12, 4:12, Control (3:12), and 6:12

Immediately after construction, and therefore before the onset of mould growth, wood treatments were applied to approximately one square foot test sections on the underside of the plywood sheathing in each roof on both the North and South orientations to assess their impact on reducing the long-term potential for fungal growth and degradation. The efficacy of the treatments was assessed visually. The first round of wood treatments applied in October 2012 were:

→ Boracol® 20-2,

→ Copper Naphthenate,

→ Bleach,

→ Thompson's WaterSeal®, and

→ Kilz® Paint.

A second round of wood treatments was applied in April 2013 after the first winter of wetting and when some mould growth was present on the sheathing; this consisted of:

→ Zinc Naphthenate, and

→ Boracol® 20-2 BD.

Boracol® is produced by Sansin Corporation and the original 20-2 formulation is a wood preservative/fungicide whereas the 20-2 BD formulation has an added mouldicide effect over the 20-2. Figure 1.13 and Figure 1.14 show these surface treatments as initially applied to the roof sheathing. Note that the second round of wood treatments were applied to the sheathing when mould growth may have already been present.

Figure 1.13 – First round application of surface treatments applied to each roof and slope. From top left, counter-clockwise: Kilz® Paint, Bleach, Thompson's WaterSeal ®, Boracol 20-2, Copper Naphthenate

Figure 1.14 – Second round application of surface treatments applied to each roof and slope. Boracol 20-2 BD (left) and Zinc Naphthenate (right)

In Part 2 of the testing, the control roof was modified to include a ventilation layer between the shingles and the self-adhered impermeable membrane. This was achieved by the removal of the shingles from the roof, sealing of nail holes in the existing membrane, and then installing a vented ½" drain mat, 3/16" asphalt board, and new shingles. This modification was made in November 2013 and the roof assembly including the drain mat is shown in Figure 1.15 and Figure 1.16.

Figure 1.15 New vented drain-mat layer installed over the existing self-adhered membrane in the control roof

Figure 1.16 New control roof with vented layer under new shingles. Vent openings are provided at the eaves.

1.2.2 Monitoring of the Roof Huts

Temperature, moisture content, and relative humidity sensors were installed in conjunction with wireless data loggers to measure the thermal and moisture profiles of the roof assemblies. A naming convention was developed to identify the sensors used in this study and the convention is described in Table 1.1.

TABLE 1.1 – SENSOR NAMING CONVENTION

Roof Hut Name			
CONT	3:12 sloped control roof with impermeable self-adhered underlay		
312	3:12 sloped roof with permeable underlay		
412	4:12 sloped roof with permeable underlay		
612	6:12 sloped roof with permeable underlay		
VENT	3:12 sloped control roof with impermeable self-adhered membrane underlay and vented drain mat layer		
Sensor Type		**Orientation**	
T	Temperature	N	North
MC	Moisture Content	S	South
COND	Condensation Sensor		
MC Sensor Position			
OUT	Measuring the MC of the outer 1/8" of the plywood sheathing		
IN	Measuring the MC of the inner 1/8" of the plywood sheathing		
FULL	Measuring the MC of the full thickness of the plywood sheathing. (Provides measurement of wettest part of the sheathing.)		
SURF	Measuring MC of inner 1/8" of the plywood sheathing using pins installed with conductive epoxy		

To monitor the moisture content of the plywood sheathing, moisture pins were installed. The placement of the moisture pins is critical in observing how wetting occurs; therefore three sets of moisture pins were installed on each orientation of each test roof. The first set of moisture pins penetrates through all layers of the plywood in order to detect the worst-case moisture content in the sheathing. The second set of moisture pins is insulated and only exposed at the upper layers (outer 1/8") of the plywood to measure wetting at the shingle side. The third set of moisture pins penetrates only the bottom layers (inner 1/8") of plywood to measure wetting at the underside (i.e. night sky condensation). This arrangement of various moisture pin depths allows for the monitoring of how moisture migrates through the plywood sheathing. The sensors are placed near the centre of the panels to eliminate edge effects. A standard gap in the roof sheathing is located above the sensors and represents a possible water penetration point. A temperature sensor for moisture content calibration is installed within a small hole drilled into mid-depth of the plywood. Figure 1.17 shows a schematic of the moisture pin installation into the plywood and Figure 1.18 through Figure 1.21 show photographs of the initially installed moisture content and temperature sensors.

Additional surface temperature, moisture content, and condensation sensors were installed in March 2013 to collect data to show night sky cooling effects and the potential for condensation/rain on the exterior of the shingles and interior surface of the plywood. The sensors were installed on the North and South slopes of the 3:12. Photographs of the installed condensation sensors are shown in Figure 1.22 and Figure 1.23. Additional moisture content sensors were installed in May 2013. These sensors were installed using conductive epoxy to provide improved contact between the moisture pins and the plywood substrate, and like the "inner" moisture pins, these were installed to measure the moisture content of the surface and inner 1/8" of the sheathing. The arrangement of these additional pins is shown in Figure 1.17.

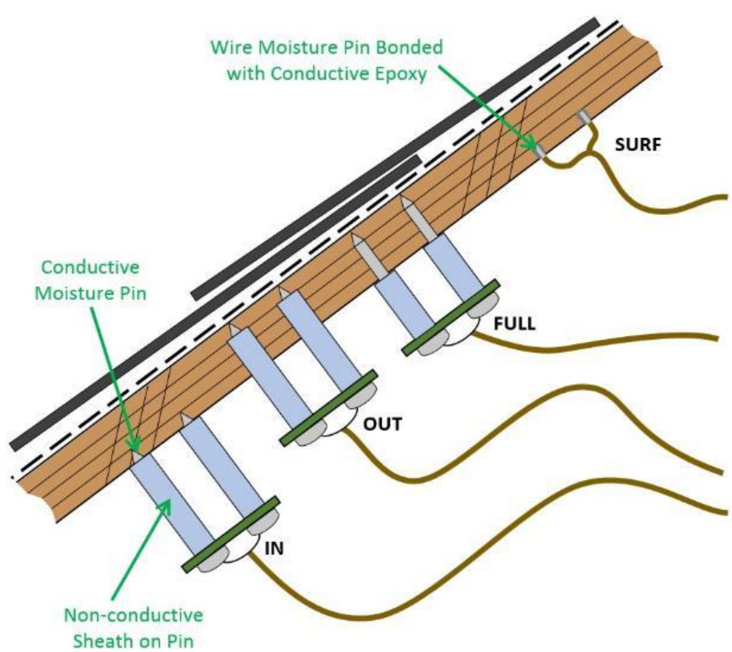


Figure 1.17 – Schematic of moisture pin installation at inner 1/8" (IN), outer 1/8" (OUT), and whole depth (FULL) of the plywood, and inner 1/8" of the plywood using pins installed with conductive epoxy (SURF).

Figure 1.18 – Overview of 6:12 roof hut South (left) and North (right) slopes

Figure 1.19 – View of underside of 4:12 roof hut showing placement of moisture pins and sheathing temperature sensors

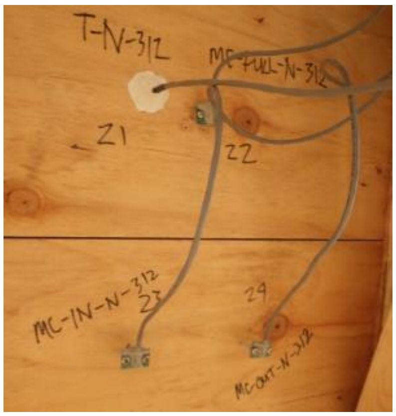


Figure 1.20 – Typical moisture pin placement for each roof (North 3:12 roof shown here). Full depth pin top left, temperature sensor top right, inner ply pin bottom left, aligned horizontally with outer ply pin bottom right

Figure 1.21 – Close up showing moisture pin stand-offs and pin insulators from inside surface of the plywood (South 4:12 roof shown here). Note gap within plywood located a few inches above these pins

Figure 1.22 – Condensation sensor and surface temperature sensors installed in March 2013 to shingle side of roof

Figure 1.23 – Condensation sensor and surface temperature sensors installed in March 2013 to interior side of sheathing

1.2.3 Laboratory Testing

To supplement the field testing portion of this study, the water uptake of the installed shingles and roofing felt along with several other commercially available asphalt shingles was investigated. Samples were fully submerged in water and the mass was recorded periodically to measure potential absorptivity of each shingle. Further research could include absorption testing of weathered shingles.

2 Results & Analysis – Standard Attic Construction

The primary objective of this study was to demonstrate that sloped wood-frame attic roofs constructed according to best practice guidelines experience moisture related problems even in the absence of interior moisture sources and with unrestricted ventilation. To this effect, this section presents the findings of the field exposure monitoring study with respect to standard attic construction arrangements.

The performance of the roof huts was monitored from September 21, 2012 to April 4, 2014; however, data is typically presented for smaller timeframes within the monitoring period to allow for more detailed analysis and to accommodate some periods of data loss. The “control” roof was modified to include a vented layer between the shingles and the self-adhered impermeable membrane underlay in November 2013. This modified roof assembly and the performance of the wood treatments are discussed in Section 3. Additional plots to supplement those provided in this section are provided in Appendix A.

2.1 Overview of Exterior Conditions

Given the pertinence of the exterior climate to the performance of the test roofs, this section provides an overview of the exterior conditions at the RDH office in Vancouver, British Columbia where the roof huts were located. These roofs were not connected to interior spaces, and consequently there are no interior conditions to report.

The temperature and relative humidity were measured throughout the duration of the monitoring period and are provided in Figure 2.1. The moisture content of wood varies with the relative humidity level to which it is exposed even in the absence of condensation or other wetting mechanisms. Consequently, using the Hailwood-Horrobin (1946) correlation, the equivalent moisture content (EMC) of the plywood sheathing can be calculated based on ambient temperature and relative humidity. This is also plotted in Figure 2.1 to demonstrate the moisture content that wood would naturally experience under these environmental conditions without additional wetting or drying.

It is generally recognized that moisture contents below approximately 20% are generally considered safe from fungal growth or wood-decay, whereas moisture contents above approximately 28% (fiber saturation) are considered at risk (Wang & Morris, 2011). Moisture contents between 20% and 28% are considered cautionary, and fungal growth and wood decay can continue if present, though cannot typically be initiated if not already active. The surface relative humidity (RH) of the air adjacent to the wood is another factor to consider and high RH levels (typically above 80% RH and in almost all cases when condensation occurs, 100% RH) can lead to surface fungal growth even if high moisture content levels are not recorded. These 20% and 28% moisture contents are indicated in Figure 2.1 and in subsequent graphs of moisture content for reference.

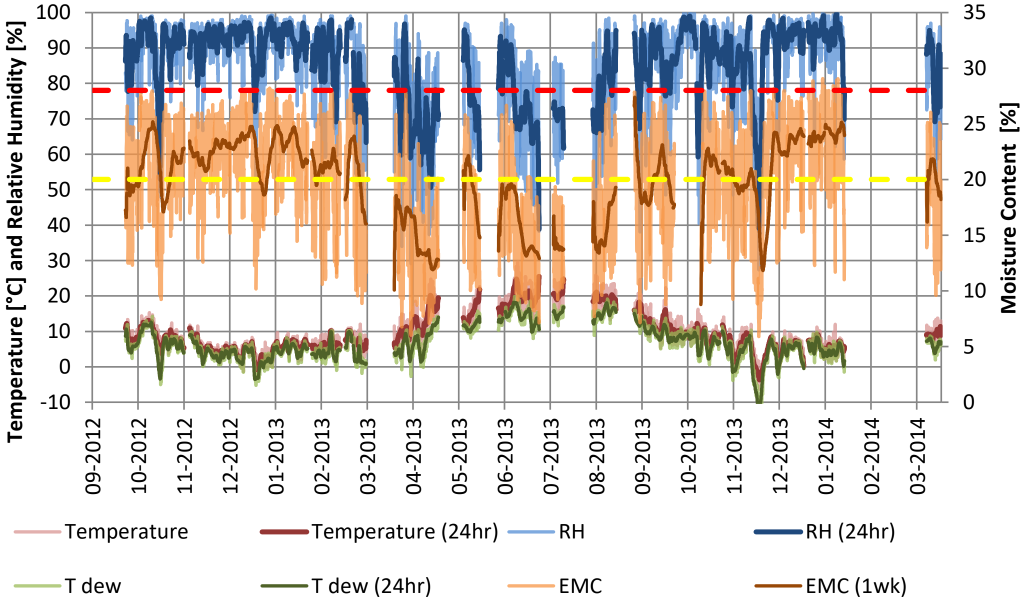


Figure 2.1 Temperature, Relative Humidity, and Equivalent Moisture Content

Reviewing the climatic data shows that the EMC exceeds 20% moisture content throughout the winter due to natural exterior temperature and humidity levels even in the absence of wetting or drying forces. Wetting and drying mechanisms, however, have the ability to both increase and decrease the moisture content of the wood relative to EMC levels. These potential wetting and drying mechanisms included precipitation and solar radiation which are plotted in Figure 2.2.

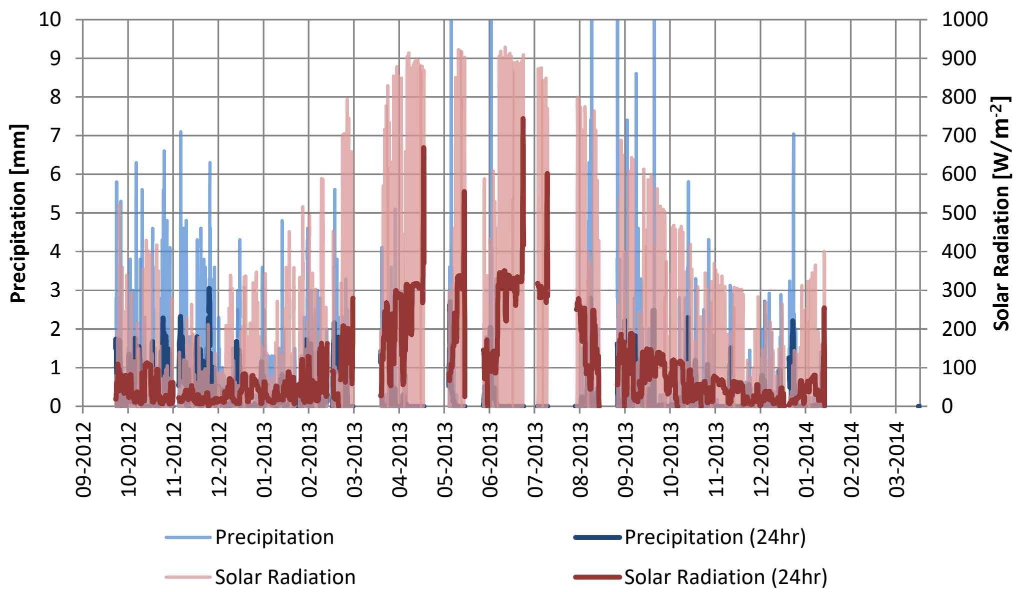


Figure 2.2– Precipitation and Solar Radiation

Consistent with the typical Pacific Northwest climate, increased precipitation occurs in the winter with less solar radiation, and in the summer there is less precipitation and significantly more solar radiation. These have pronounced effects on the performance of the test roofs as discussed in subsequent sections.

2.2 Long-Term Sheathing Moisture Balance

The moisture contents of the plywood in the roof huts is influenced by a number of factors including the ambient outdoor relative humidity, surface temperatures (e.g. due to solar radiation and radiation to the night sky), and inward vapour drive. Unlike an attic, these roof huts are not impacted by potential moisture from warm humid indoor spaces (air leakage or vapour diffusion), are not warmed by heat loss from the interior space, and are subjected to unrestricted ventilation.

Comparison of the measured MC to the calculated EMC can provide insight into whether additional wetting or drying forces were acting on the sheathing. When the MC is above the EMC it is likely that additional wetting occurred, and when the MC is below the calculated EMC, it is likely that additional drying occurred. The monitored values for the full depth moisture content pins for each of the three roof slopes and the control are presented in Figure 2.3 and Figure 2.4. Note that the EMC values presented in these plots are the same in both figures because they are calculated based on environmental conditions. The EMC values are also weekly averages, to account for the buffering effect of the moisture storing capacity of the wood sheathing. Additional plots broken down by orientation and slope are provided in Appendix A. In these figures the dashed red line indicates the critical moisture content for decay (28%) and the dashed yellow line indicates the threshold for elevated moisture content for fungal growth (20%). Error readings were omitted from the plots.

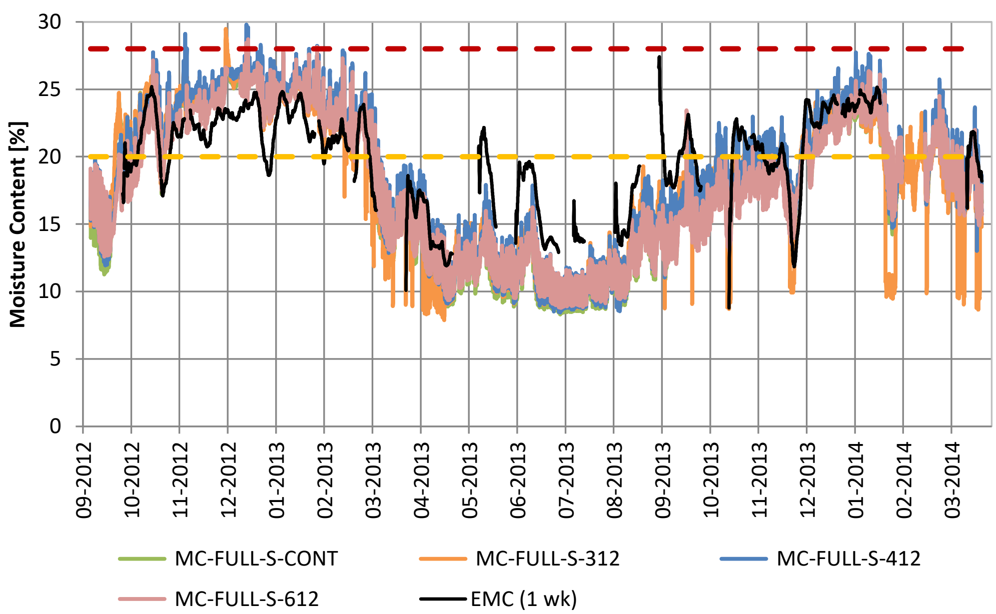


Figure 2.3– Moisture Content of Plywood Sheathing – South, Full Depth Pins – Year 1

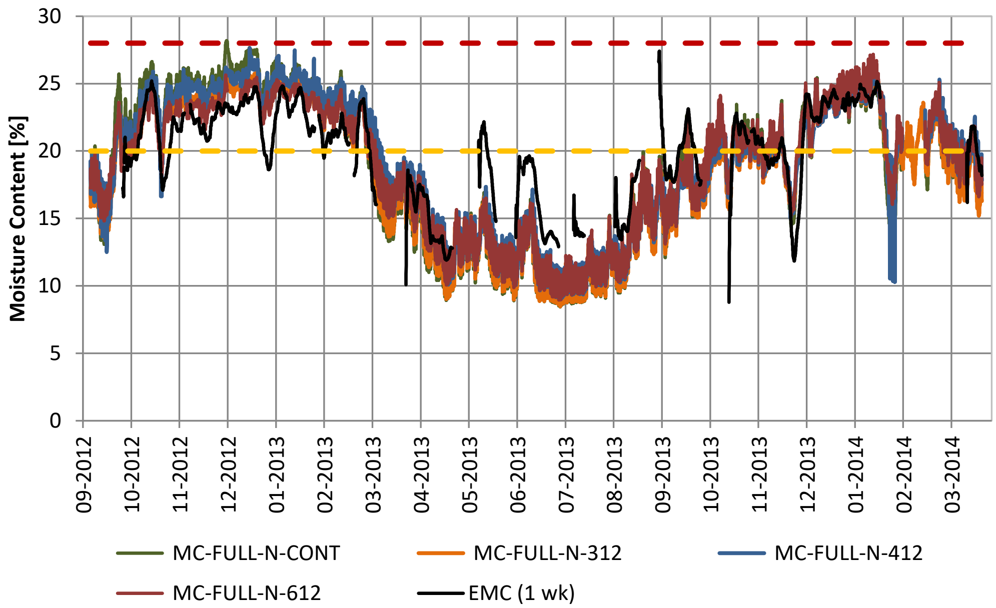


Figure 2.4 – Moisture Content of Plywood Sheathing – North, Full Depth Pins – Year 1

The moisture content of the plywood in all of the roof huts appears to be most influenced by the ambient outdoor equilibrium moisture content levels. Moisture contents at all locations range between 20% and 30% during the rainy fall through spring months of October through April. The plywood moisture content at the start of the monitoring period in early fall started at 15% MC on average, increasing to above 20% in October, up to 30% at worst case conditions in December and January. The moisture content is consistently maintained at cautionary levels for fungal contamination (above 20%) for the entire winter period. These high moisture contents are consistent with monitored data from other projects in the Lower Mainland.

In comparison with the equilibrium moisture contents (EMCs) generated from the ambient temperature and relative humidity, evidence of wetting and drying effects are apparent. Elevated moisture contents in the winter exceed the calculated EMC, suggesting wetting in addition to sorption due to ambient humidity levels. Conversely, summer moisture contents are lower than EMC values, suggesting additional drying.

Figure 2.5 provides the average seasonal moisture contents of the sheathing for each of the roof huts for the full depth moisture content sensors in both the North and South orientation. Figure 2.6 and Figure 2.7 show the results for the inner and outer sheathing moisture content pins respectively.

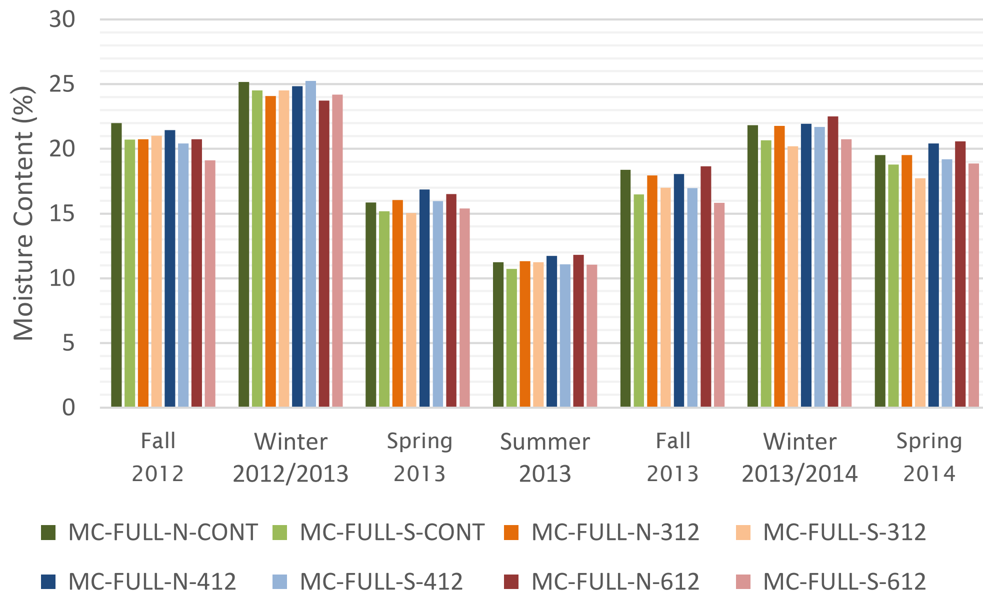


Figure 2.5– Seasonal Average Sheathing Moisture Content for North and South Elevations– Full Depth

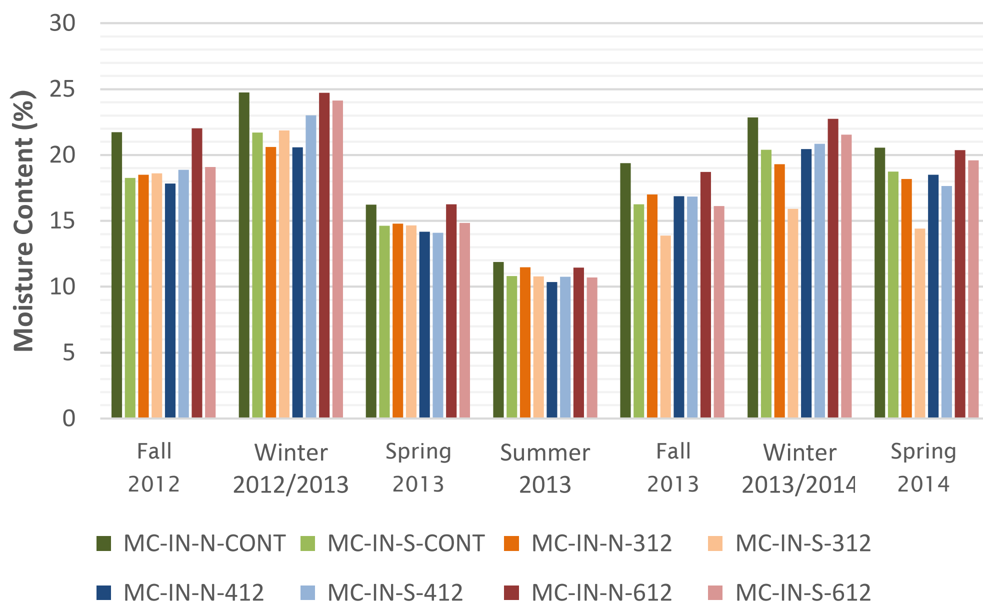


Figure 2.6– Seasonal Average Sheathing Moisture Content for North and South Elevations– Inner 1/8" Depth

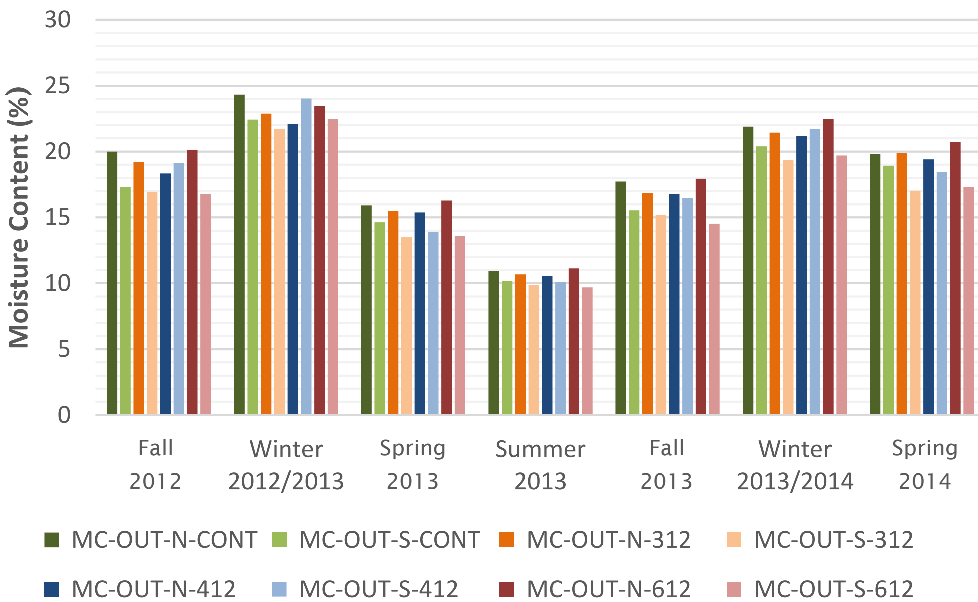


Figure 2.7– Seasonal Average Sheathing Moisture Content for North and South Elevations– Outer 1/8" Depth

The seasonal trends show summer-time drying and winter-time wetting consistent with the hourly trends shown previously in Figure 2.3 and Figure 2.4. In addition, the North exposure is generally wetter than the South exposure, with a more pronounced difference for the more steeply sloped roofs. Importantly, all three roof pitches experienced elevated moisture contents at certain times of the year, and the variation of the moisture content between roof pitches is not large enough to impact this more general trend.

As a result of these prolonged periods of elevated moisture contents, one would expect that fungal growth would occur on the underside of the roof sheathing. This anticipated fungal growth was confirmed visually on all of the test roofs as shown in Figure 2.8 and Figure 2.9. The wetting and drying mechanisms which cause the observed moisture contents and resultant fungal growth are examined in the following section.

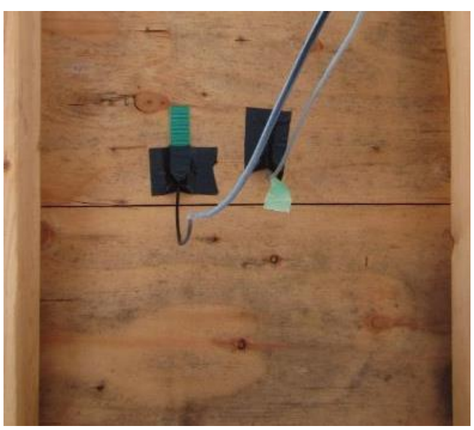


Figure 2.8 Fungal growth on the underside of the North orientation of the 3:12 roof including two areas with surface treatments which are discussed in later sections of this report

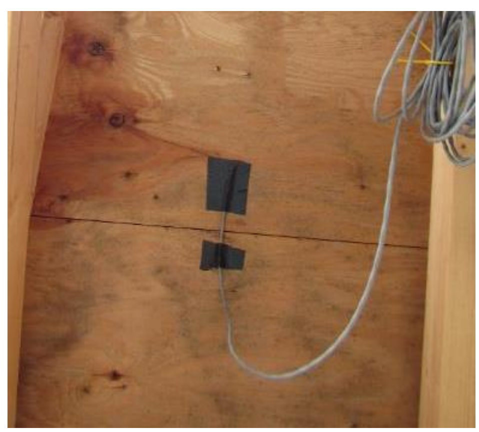


Figure 2.9 Fungal growth on the underside of the North orientation of the 4:12 roof including two areas with surface treatments which are discussed in later section of this report

2.3 Evaluation of Wetting & Drying Mechanisms

The increased moisture contents measured during colder periods and decreased moisture contents measured in warmers periods as compared to the EMC indicate that additional wetting and drying mechanisms are occurring beyond the moisture balance with ambient exterior relative humidity and temperature. It is hypothesized that these mechanisms potentially include wetting due to condensation caused by night sky cooling, wetting due to inward driven vapour caused by solar heat gains, and drying due to solar heat gains.

To examine these potential wetting and drying mechanisms, moisture contents and temperatures were analysed. Figure 2.10 shows the diurnal temperature and moisture content variations of the 3:12 North facing roof for two nights that experience condensation (October 3 and 4), and others that do not experience condensation. Instances when the interior surface temperature of the sheathing drops below the dew point temperature of the ambient air are highlighted in blue and indicate instances when condensation would theoretically occur on the underside of the sheathing.

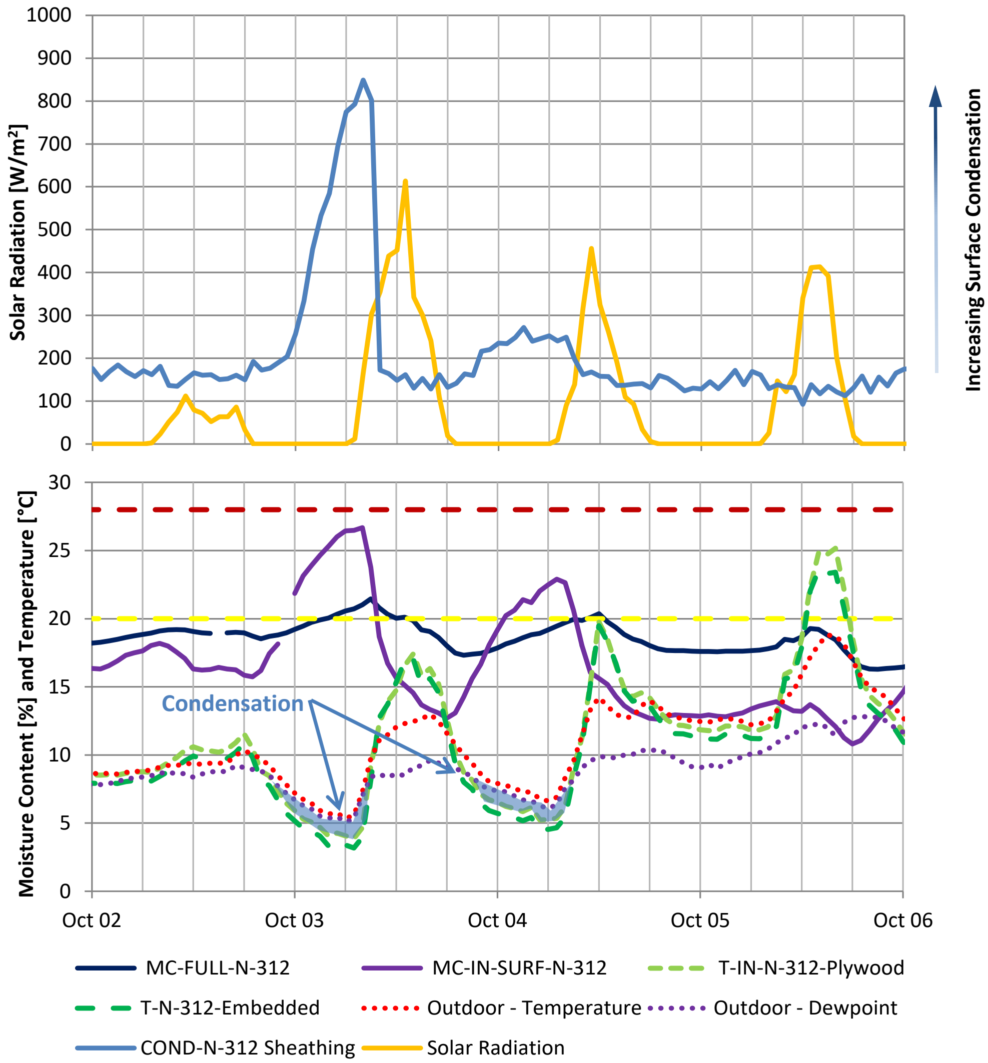


Figure 2.10 – Diurnal temperature and moisture content variation in the North 3:12 roof on October 2 to October 6, 2013.

These figures indicate diurnal cyclical wetting and drying of the plywood sheathing with wetting occurring at night and drying occurring during the day. It is important to note that the wetting of these roofs occurs primarily during the night when exposed to night sky cooling. The sheathing temperature responds quickly to exposure to solar radiation and does not exhibit significant thermal lag as a result of thermal mass.

While the full-depth moisture content of the sheathing does not vary appreciably, the surface moisture content measurements, which measure the innermost fibres of the plywood, exhibit significant diurnal variations. Wetting events occur when the temperature of the sheathing drops below the dew point temperature of the ambient outdoor air, and drying occurs as solar radiation heats the roof surface. This drying effect can be noted on both the North and South orientations, and causes the moisture content of the roofs to drop by approximately 10%. However, nighttime condensation increases the surface moisture content by a similar amount.

Night sky cooling, drying due to solar heat gains, and potential wetting from inward vapour drive are discussed in the subsequent sections.

2.3.1 Night Sky Cooling

Night sky cooling of the roofs is caused by the cold night sky absorbing infrared radiation emitted by the roofs. The degree of cooling depends on several factors, including primarily the angle of the roof (view of the night sky), and the relative temperatures of the roof surface and of the night sky as described by the Stefan-Boltzmann equation shown in Figure 3.1.

$$Q = F_{material} \cdot F_{view} \cdot \sigma \cdot \left(T_{shingles}^4 - T_{sky}^4\right) \qquad \text{Equation 2-1}$$

Q = Heat Flow [W/m²]
$F_{material}$ = Material Factor [unitless]
F_{view} = View Factor [unitless]
σ = Stefan-Boltzmann Constant [5.67×10^{-8} W/m²·K⁴]
$T_{shingles}$ = Temperature of Shingles [K]
T_{sky} = Temperature of the Sky [K]

The absorption of radiation from the sun during the day which increases the roof temperature, and then radiation of energy to night sky at night which decreases the roof temperature are shown schematically in Figure 2.11

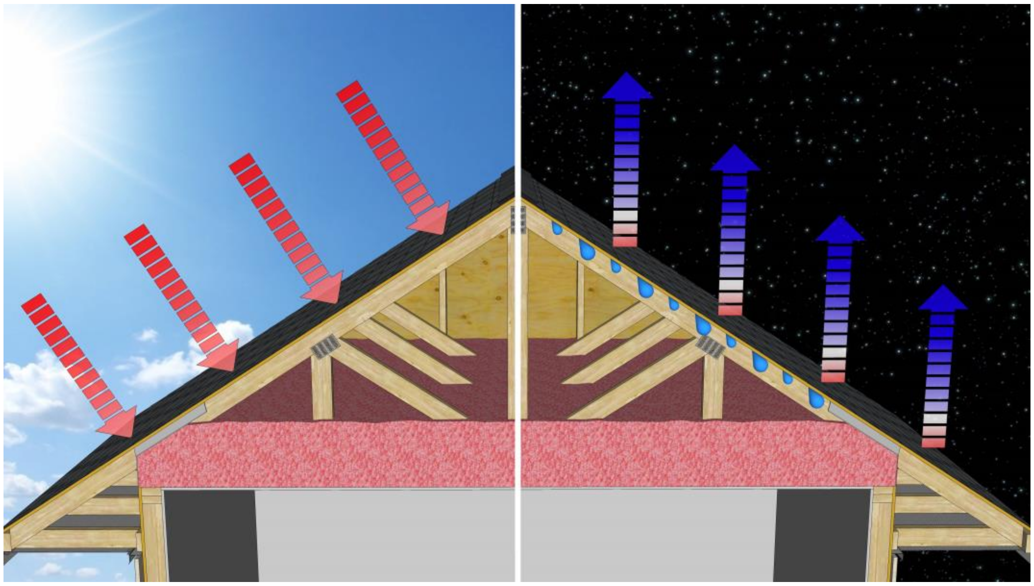


Figure 2.11 – Graphic illustrating solar radiation absorbed during the day and night sky cooling of the roof due to radiation of energy to the relatively colder night sky

The sky temperature has been correlated to good agreement following the Berdahl and Martin (1984) correlation, which relates sky temperature to ambient temperature, ambient air dew point temperature, and time of day. Following this relationship, sky temperatures may fluctuate anywhere from extremes of 5-30°C cooler than ambient conditions. However, the presence of cloud cover can significantly alter the apparent sky temperature as heat is reflected back to the ground from the water particles. The *material factor* ($F_{material}$) relates to the degree to which the materials are capable of absorbing and emitting radiation. The *view factor* (F_{view}) depends on how much the roof surface is exposed to the sky. A flat roof is entirely exposed to the night sky and will have a larger view factor than a steeply sloped roof which will also have some exposure to the ground, which is much warmer than the sky.

This night sky cooling depresses the temperature of the roofs below the ambient air temperature, and in some cases can also depress the roof temperature below the dew point of the ambient air and cause condensation (and frost when below freezing). By measuring the temperature depression of the roof shingles compared to ambient temperatures, the degree of night-sky cooling can be quantified. The view-factor of the roof, emissivity of the roof surface, previous precipitation events, and thermal storage of the roof assembly all have an impact on the degree of temperature depression.

Night sky cooling and subsequent condensation and frost formation was confirmed visually at various times during the study and an example of typical observations made on January 2, 2013 are provided in Figure 2.12 to Figure 2.15.

Figure 2.12 – Frost on exterior of shingles during morning of January 2, 2013

Figure 2.13 – Frost on exterior of shingles on North orientation but not on South orientation showing the impact of rising sun during morning of January 2, 2013

Figure 2.14 – Frost on nail heads of South facing roof slope on morning of January 2, 2013

Figure 2.15 – Condensation on underside of plywood sheathing on morning of January 2, 2013. Note that surface condensation at this time is only visible on certain areas of the plywood and was affected by wood grain.

Interestingly condensation was mostly visible on areas of the plywood made of heartwood. This is likely because these areas are denser, and potentially include more water repellant extractives; consequently, the surface condensation absorbs less quickly in these areas than it does in the sapwood areas. Two photos further illustrating this effect are provided in Figure 2.16 and Figure 2.17 from October 3, 2013.

Figure 2.16 – Condensation on the underside of the roof sheathing on October 3, 2013 showing a location where it has been absorbed by the sapwood but has not been absorbed by the heartwood.

Figure 2.17 – Condensation on the underside of the roof sheathing on October 3, 2013 showing a location where extractives from the wood sheathing are visibly noticeable in the condensation droplets

The shingles were visually noted to have significantly more condensation (or frost) than the underside of the sheathing, and this was confirmed by the condensation sensors installed on the 3:12 roof as shown in Figure 2.18. It is important to note that while in many cases the measured moisture is condensation (or frost) due to night sky cooling, the shingle condensation sensor is also exposed to wetting by precipitation.

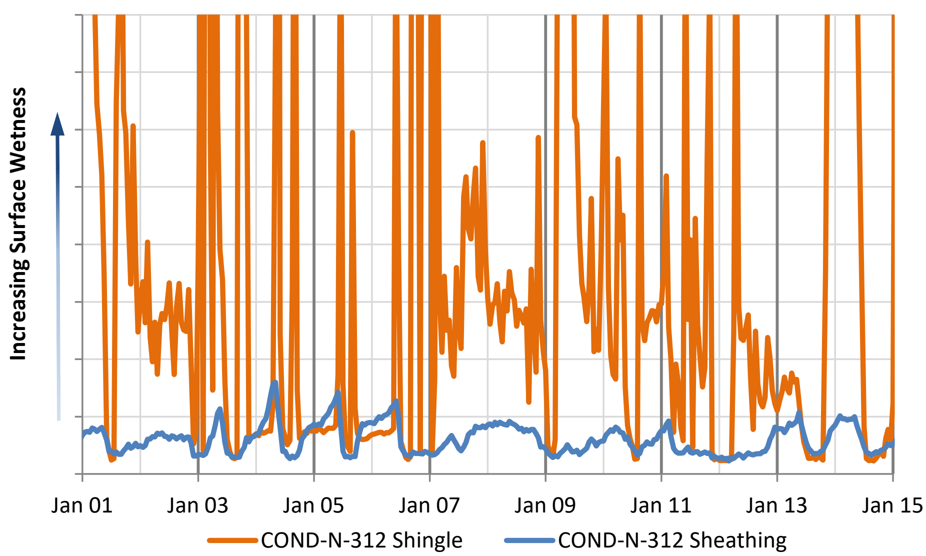


Figure 2.18 – Shingle and Sheathing Condensation Sensor Readings from January 1 to January 15, 2014

The occurrence of more condensation on the shingles is likely because night sky cooling acts directly on the shingles which are exposed to the night sky, while the sheathing is cooled secondarily due to heat transfer through the roof assembly. Consequently, the sheathing temperature is buffered by the thermal resistance of the roof assembly and is typically cooled less than shingles.

To further assess the cooling of the shingles and sheathing, the average night temperature depressions, defined as the decrease in shingle and sheathing temperatures below ambient air, were calculated for the periods when no solar radiation was measured (i.e. nighttime) and the results are provided in Figure 2.19.

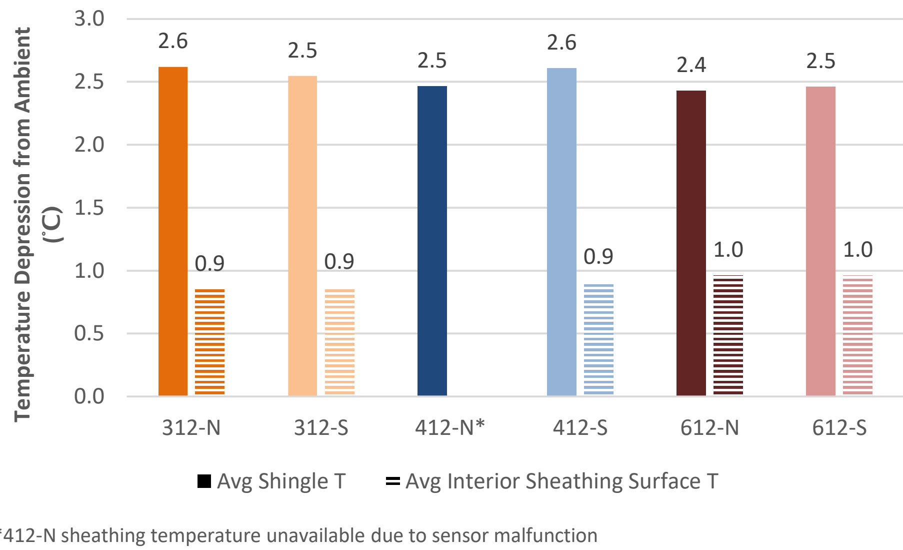
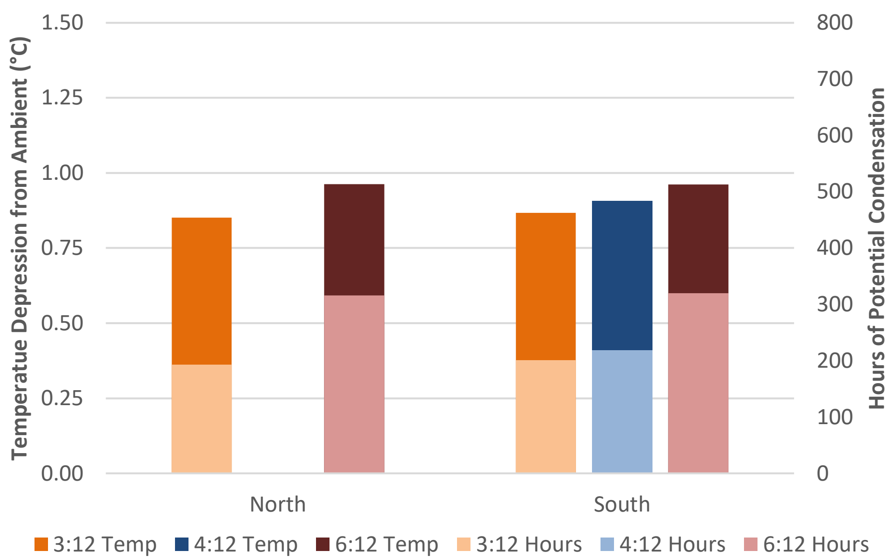


Figure 2.19 – Average Shingle and Sheathing Temperature Depression compared to Ambient Temperature for Winter (December 1, 2013 to January 31, 2014).

A small difference was observed between the roof shingle temperatures on the 3:12/4:12 roofs compared to the 6:12 roof, with the 6:12 typically experiencing less cooling that the other two roof slopes. This follows logically from the 6:12 roof being less exposed (lower F_{view}) to night sky radiation. The variation in the sheathing temperatures according to roof slope is much less pronounced than the variation in the shingle temperatures. Interestingly, the 6:12 pitches experience a greater sheathing temperature depression than the less inclined roof pitches. The cause of this difference requires further investigation.

To further assess the effects of night sky cooling, an analysis of the total number of hours of potential condensation was conducted, and the results are provided in Table 2.1. A histogram of the number of potential hours of condensation is also shown in Figure 2.20, with the darker coloured bars representing the sheathing temperature depression relative to ambient conditions, and the lighter coloured bars representing the number of hours of potential condensation based on ambient dew-point temperatures. The control roof was omitted from this analysis as at this point in the monitoring a vented layer was included and would impact the temperature results.

TABLE 2.1 – NUMBER OF HOURS OF POTENTIAL CONDENSATION FOR DECEMBER 2013 TO JANUARY 2014			
ROOF	**NUMBER OF HOURS OF POTENTIAL CONDENSATION**	**TOTAL NUMBER RECORDED HOURS**	**PERCENT TIME FOR MEASURED PERIOD**
3:12 North Orientation	193	1394	14
3:12 South Orientation	201	1394	15
4:12 North Orientation	-	-	-
4:12 South Orientation	219	1395	16
6:12 North Orientation	316	1396	23
6:12 South Orientation	320	1396	23



*412-N sheathing temperature unavailable due to sensor malfunction

Figure 2.20 – Number of Hours of Potential Condensation and Average Night-Time Sheathing Temperature Depression from Ambient for North and South Oriented Roofs for 3:12, 4:12, 6:12, and Control Roofs from December 1, 2013 to January 31, 2014

Figure 2.20 shows a slight difference in sheathing temperature between the 6:12 roof and the 3:12/4:12 roofs. Despite being less exposed to the night sky, the 6:12 roof assemblies experience an increased number of hours of potential condensation.

To further investigate why the 6:12 roof was calculated to experience more hours of condensation than the other roofs, the hourly potential for condensation is provided for a two week period in January 2014 in Figure 2.21. This figure illustrates that the 6:12 roof frequently experiences an additional hour of potential condensation at both the beginning of the night and at the end of night. While the cause has not be confirmed, it is possible that the positioning of the test roofs caused the 6:12 roof to be shaded by an adjacent building when the sun was at a low angle, consequently extending the period for which condensation could occur on the roof.

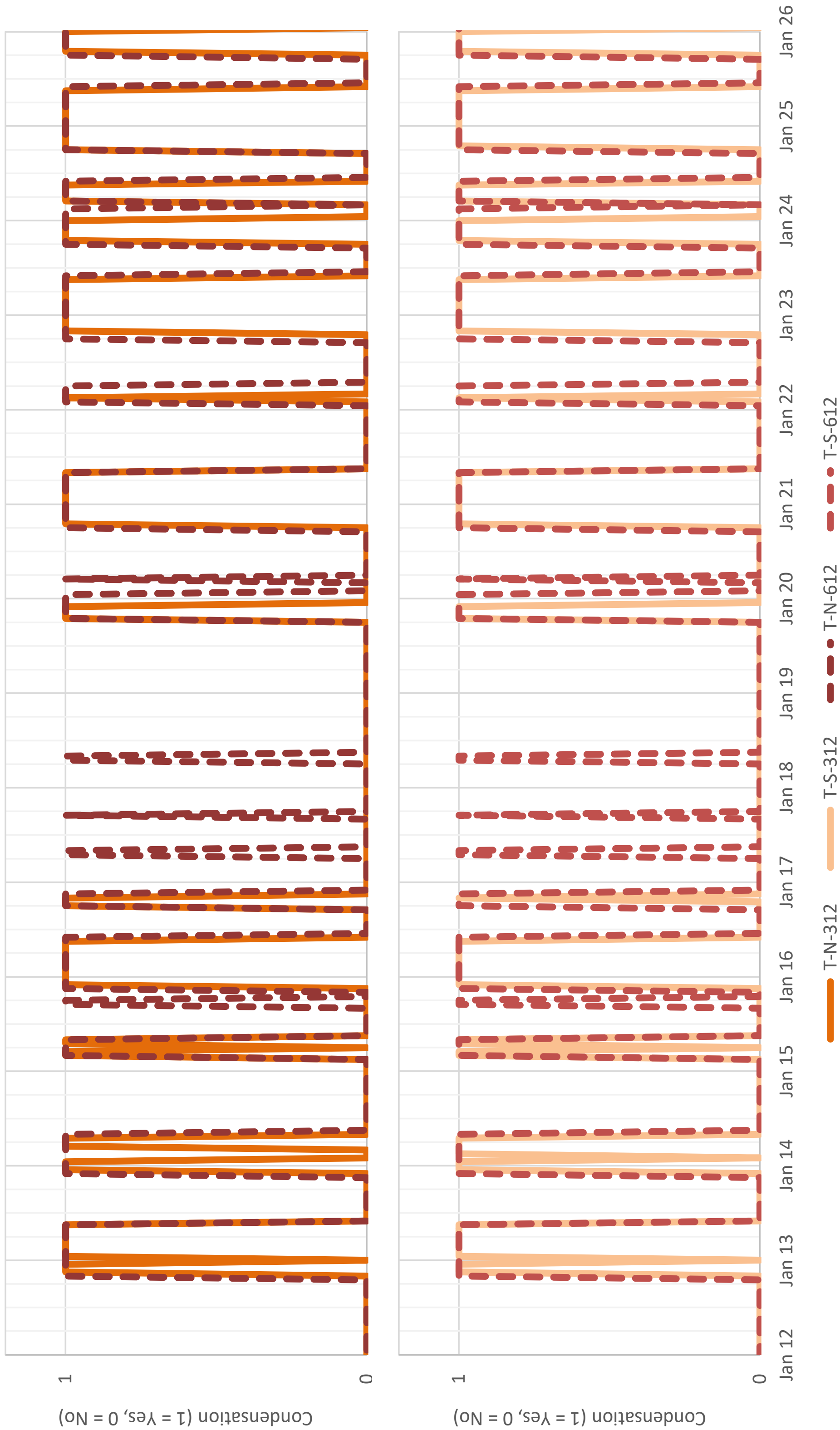


Figure 2.21 – Hours of Potential Condensation for 3:12 and 6:12 Roofs from January 12, 2014 to January 26, 2014

Overall, condensation of moisture from the ambient outdoor air was observed on all of the test roofs due to night sky cooling of the roof sheathing. This cooling and consequently wetting mechanism significantly impacted the moisture content of the roof sheathing and contributed to prolonged periods of moderate to high moisture contents during which fungal growth can be supported and/or initiated. Consequently, it is likely that night sky cooling, and associated condensation, is a significant contributor to the moisture problems observed in sloped wood-frame attic roof assemblies. These problems were observed on the test roofs despite elimination of other wetting mechanisms and unrestricted ventilation.

2.3.2 Solar Heat Gain

Roof slope not only impacts the exposure to the night sky, it also impacts the amount of solar radiation which is incident on the roof surface. Solar radiation is absorbed by the roofs which significantly increases the roof temperature above the ambient air temperature and can act to dry the roof sheathing. Roofs that are angled such that they absorb more solar radiation will be hotter, and consequently, likely dryer than otherwise. To demonstrate this temperature rise due to the absorption of solar radiation, the temperature of the shingles and of the interior sheathing surfaces for the 3:12 and 6:12 roofs are provided in Figure 2.22 over the course of a typical sunny summer day.

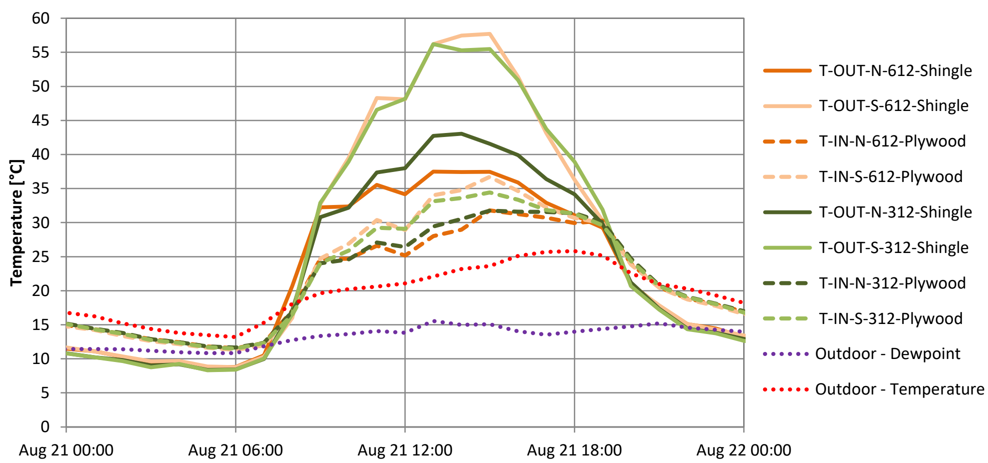


Figure 2.22 – Exterior Shingle and Interior Plywood Surface Temperatures compared to Outdoor Conditions, August 21, 2013

Figure 2.22 illustrates that the temperature of both the shingles and the plywood sheathing is often significantly warmer than the ambient air temperature which can dry the sheathing and reduce the potential for fungal growth.

The average shingle and sheathing temperature rise above ambient were calculated to assess the average impact of solar heat gains on the roof temperatures. The results, shown in Figure 2.23, demonstrate the significant impact of orientation on the temperature rise for the roof assemblies, and the significant but lesser impact of roof slope.

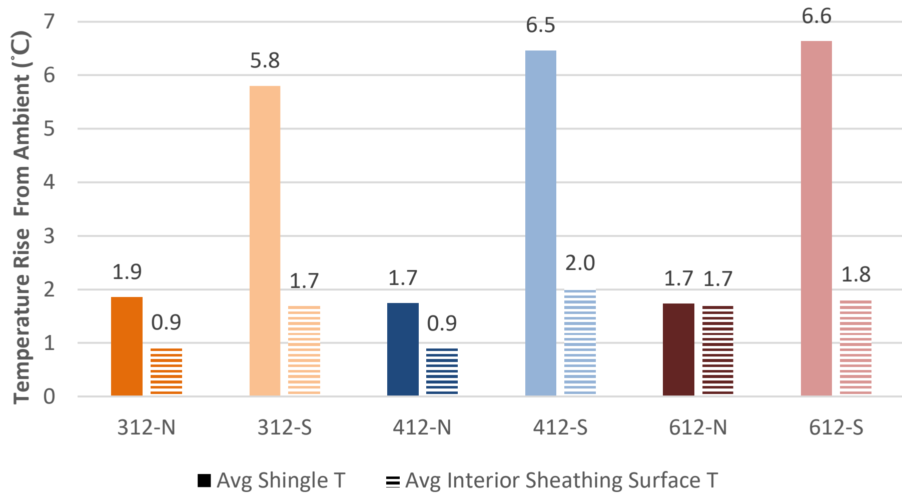


Figure 2.23 – Average Shingle and Sheathing Temperature Rise Above Ambient for Winter 2013/2014.

As one would expect, the 6:12 South oriented roof experiences the highest average shingle temperature rises above ambient, followed by the 4:12 roof and then the 3:12 roof. The increased temperatures and consequently drying potential on the South orientations as compared to the North orientations is consistent with the previously presented moisture contents (see Figure 2.5) which indicate that the North orientations are typically wetter than the South orientations. Interestingly, the 6:12 North roof sheathing temperature rise is approximately the same as the South orientation. The cause of this is unknown, but may be a result of the potential capture of warm air in the roof hut ridge.

The increased surface temperatures measured on the South roof orientations also resulted in better self-sealing of the shingle laps as is shown in Figure 2.24 and Figure 2.25. This improved sealing may potentially reduce ingress of water through the shingles as well as the potential for storage of water between the shingle layers.

Figure 2.24 – Poor self-sealing at majority of shingle tabs on North slope observed for several months after installation.

Figure 2.25 – Self-sealing at majority of shingles on South slopes observed within weeks after installation

2.3.3 Inward Vapour Diffusion & Outward Drying

To assess the potential for wetting due to inward vapour diffusion and the potential impact of restricted outward drying, two types of underlayment were considered as part of this research: a permeable #15 roof felt, and an impermeable self-adhered membrane. The vapour permeable #15 roof felt has a vapour permeance that ranges from approximately 0.5 U.S. perms (29 ng/s·m²·Pa) under dry conditions up to 30 U.S. perms (1720 ng/s·m²·Pa) in wet conditions (Straube and Burnett, 2005). The vapour impermeable self-adhered membrane has a maximum vapour permeance of approximately 0.1 U.S. perms (6 ng/s·m²·Pa). An impermeable membrane eliminates any sources of exterior wetting, but also eliminates the potential for outward drying. The vapour permeable membrane allows for some vapour diffusion which may result in some degree of wetting from and drying to the exterior. Photos of the two different underlays were provided previously in Figure 1.8 and Figure 1.9.

The vapour impermeable (control) and permeable (3:12) roof specimens were compared to assess the impacts of the permeance of these underlayments on the wetting and drying characteristics of the roof assemblies. The moisture content of the outer sheathing layer for the impermeable and permeable roof assemblies are shown in Figure 2.26 and Figure 2.27, for the South and North orientations, respectively.

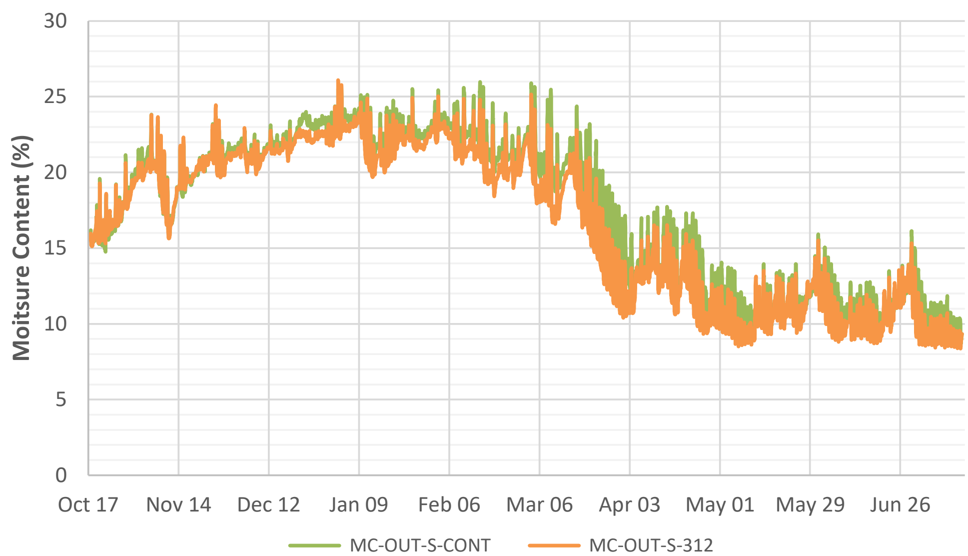


Figure 2.26 – Moisture Content of Outer 1/8" of Sheathing for Impermeable (CONT) and Permeable (312) Underlayment, South Elevation

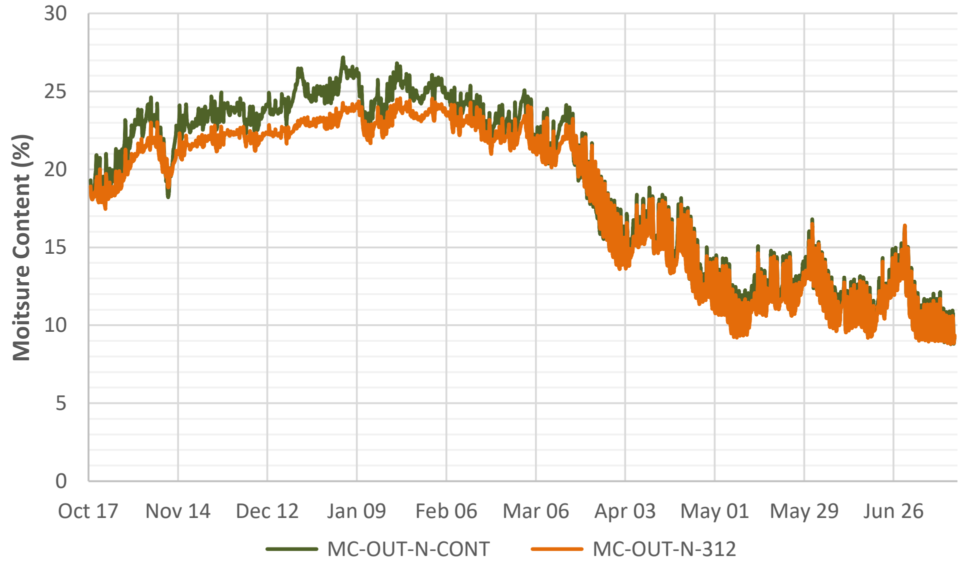


Figure 2.27 – Moisture Content of Outer 1/8" of Sheathing for Impermeable (CONT) and Permeable (312) Underlayment, North Elevation

Figure 2.26 and Figure 2.27 indicate that the outer moisture content in the vapour impermeable assembly is consistently wetter than the permeable assembly, in particular on the North orientation. This is illustrated here using the moisture content of the outer part of the sheathing; however, moisture content measurements of the interior layer are consistent with this finding and graphs are provided in Appendix A. The increased moisture content of the sheathing in the control roof is likely a result of the inability of the sheathing to dry to the exterior. This finding suggests that exterior wetting from saturated shingles is not a significant cause of wetting of the exterior of the assembly and that instead the reduced outward drying increases the moisture content of the sheathing. However, this finding is for small, well-constructed, new roofs with no penetrations. Larger, less well-constructed, aged roofs which include penetrations are more typical of actual construction practice, and in these cases the improved water ingress resistance provided by the self-adhered membrane as compared to the roofing felt would likely outweigh the potential reduction in drying capacity.

2.4 Water Uptake Laboratory Testing

Water absorption testing of the asphalt shingles was performed as part of the study to better understand the impact of shingle wetting on moisture uptake through the sloped roofs. While a submerged test is not indicative of the moisture that may be absorbed in-service on a sloped roof, it does provide some insight into the water absorption capacity of the shingles.

Water absorption of the roof underlayment, in this case #15 roofing felt, was also performed at the same time. Results are provided in Figure 2.28 and Table 2.2.

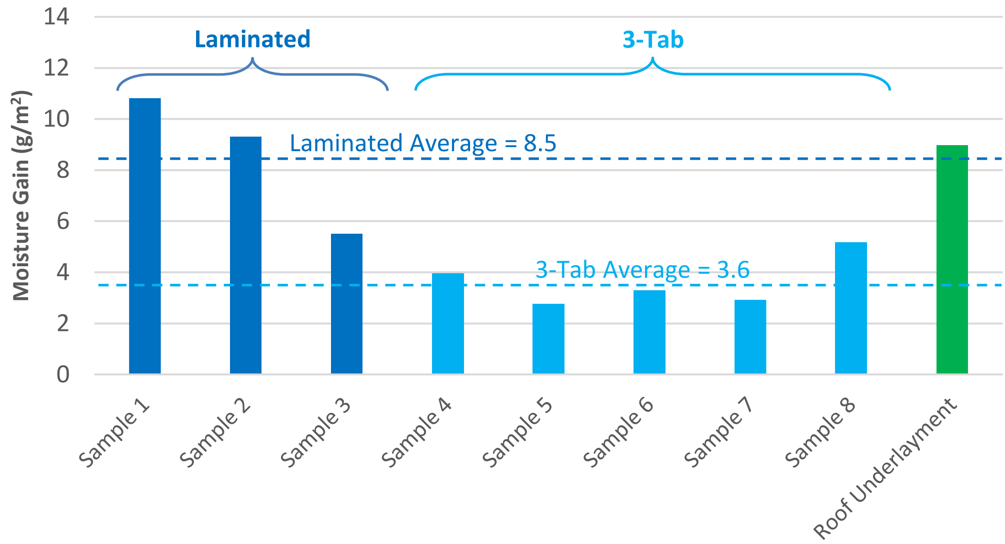


Figure 2.28– Moisture Uptake for 8 Shingle Products and Roof Underlayment

TABLE 2.2 – SUBMERGED SHINGLE WATER ABSORPTION TEST RESULTS (128 DAYS)			
Sample	**Type**	**Absorption (after 128 Days)**	
		[%]	**[g/m²]**
Sample 1	Laminated	6.1%	10.81
Sample 2	Laminated	4.8%	9.31
Sample 3	Laminated	3.2%	5.51
Sample 4	3-Tab	2.5%	3.96
Sample 5*	3-Tab	1.8%	2.77
Sample 6	3-Tab	2.8%	3.29
Sample 7	3-Tab	1.7%	2.92
Sample 8	3-Tab	3.0%	5.16
Roof Underlayment*	#15 roofing felt	61%	8.97

* Shingles and underlay installed on study roof huts

The results of the water uptake testing clearly illustrate that laminated shingles absorb more water than do 3-tab shingles when submerged in water for 128 days. The increased moisture storage capacity of laminated shingles could potentially impact roof performance; however, analysis of in-service performance of different shingle types is beyond the scope of this study.

2.5 Summary of Findings – Standard Attic Construction

The key findings with regards to the performance of industry standard sloped wood-frame attic roof assemblies are summarized here.

→ The roof sheathing in well ventilated (i.e. outdoor exposed attics, canopies, or soffits) experience elevated moisture contents above 20% and periodically above 28% for significant portions of the year which creates significant risk of fungal growth on these assemblies. These moisture contents occurred despite the elimination of typical wetting mechanisms including rain water ingress, air leakage from interior space or ductwork, and re-entrainment of humid exhaust air into the vented attic space, and the provision of unrestricted ventilation. While in large part the elevated moisture contents measured are due to the plywood reaching equilibrium with ambient temperature and relative humidity conditions, often the sheathing moisture content was measured above the equilibrium moisture content indicating the presence of additional wetting mechanisms.

→ Measured sheathing moisture contents in the summer are frequently less than the calculated equilibrium moisture content indicating that additional drying mechanisms are acting on the sheathing.

→ Fungal growth was observed on both the North and South orientations of all of the test roofs despite decoupling from interior sources of moisture including leakage of interior air and the provision of unrestricted ventilation.

→ Night sky cooling can cause condensation (and in some cases frost) on the underside of the roof sheathing due to depression of sheathing surface temperatures below the dew point temperature of the exterior air. The degree to which the sheathing temperature is depressed depends on a number of factors including the thermal resistance and heat capacity of the roofing materials, and the length of the cooling event. This wetting mechanism was found to be a significant contributor to increased sheathing moisture contents, facilitating fungal growth.

→ Typically more fungal growth occurred on the North roof orientations than on the South orientations, likely as a result of increased solar heat gains of the South roof assemblies which facilitate drying.

→ The installation of an impermeable sheathing underlay leads to increased sheathing moisture contents compared to the roofs with permeable underlays likely due to the restriction of outward drying. In reality, however, more realistic roofs with aged shingles and penetrations may benefit from the increased water penetration resistance of the impermeable membrane and this benefit may outweigh the potential negative effects of restricted outward drying.

→ Laminated shingles absorb significantly more water than do 3-tab shingles and this creates a potential moisture reservoir which may impact roof performance.

3 Results & Analysis – Mitigation Strategies

Section 2 demonstrates that sloped wood-frame attic roof assemblies as currently constructed have significant risk of fungal growth and degradation due to elevated moisture contents, and that this cannot be prevented by ventilation alone. This section evaluates two potential mitigation strategies: a vented underlay layer, and wood preservative treatments.

3.1 Vented Underlay

In Part 2 of the testing, the control roof was modified to include a ventilation layer between the shingles and the self-adhered impermeable membrane. This was achieved by the removal of the shingles from the roof, sealing of nail holes in the existing membrane, installation of a 1/2" drain mat, installation of a 3/16" asphalt board, and installation of new shingles. This modification was made in November 2013. To differentiate between the original control assembly and the modified assembly, the vented control roof will be referred to as "VENT."

It has been hypothesized that venting the top of the sheathing could reduce the impact of night sky cooling by decoupling the sheathing from the shingles which experience the night sky cooling directly. However, this vented layer may also decrease the drying of the sheathing by decreasing the transfer of solar heat gains from the shingles to the sheathing. This trade-off between decreased wetting and decreased drying is analysed in this section.

Figure 3.1 and Figure 3.2 provide the shingle and interior sheathing surface temperature on the North and South orientations of the vented roof and the standard 3:12 roof. These figures indicate that for both the North and South orientations, the 3:12 roof experiences more extreme shingle and plywood temperatures than the control roof. This difference is more pronounced on the South orientation, and is also more pronounced for maximum daily temperatures than it is for minimum daily temperatures. These findings suggest that the vented layer provides some transfer of heat by bulk air movement and/or some insulation between the shingle temperatures and the sheathing. In either case, the result is that the sheathing of the vented roof is maintained at a temperature closer to ambient temperature and is less impacted by both night sky cooling and solar heat gains.

A closer review for a period from January 16 to January 18, 2014 more clearly shows the impact of the vented layer on assembly temperatures. This is shown for the North orientations in Figure 3.3 and South orientations in Figure 3.4.

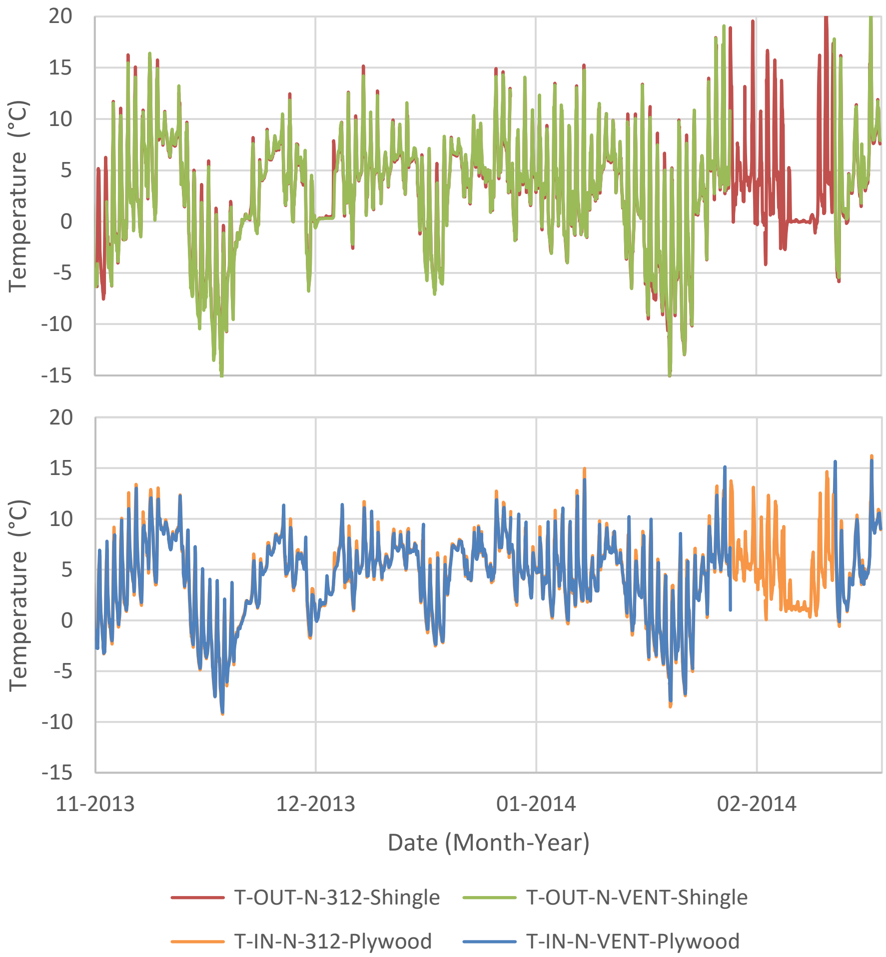


Figure 3.1– Shingle and Plywood Sheathing Temperatures for Top-Vented (Vent) and Standard Roof (3:12 Pitch with Roofing Paper) – North Orientation

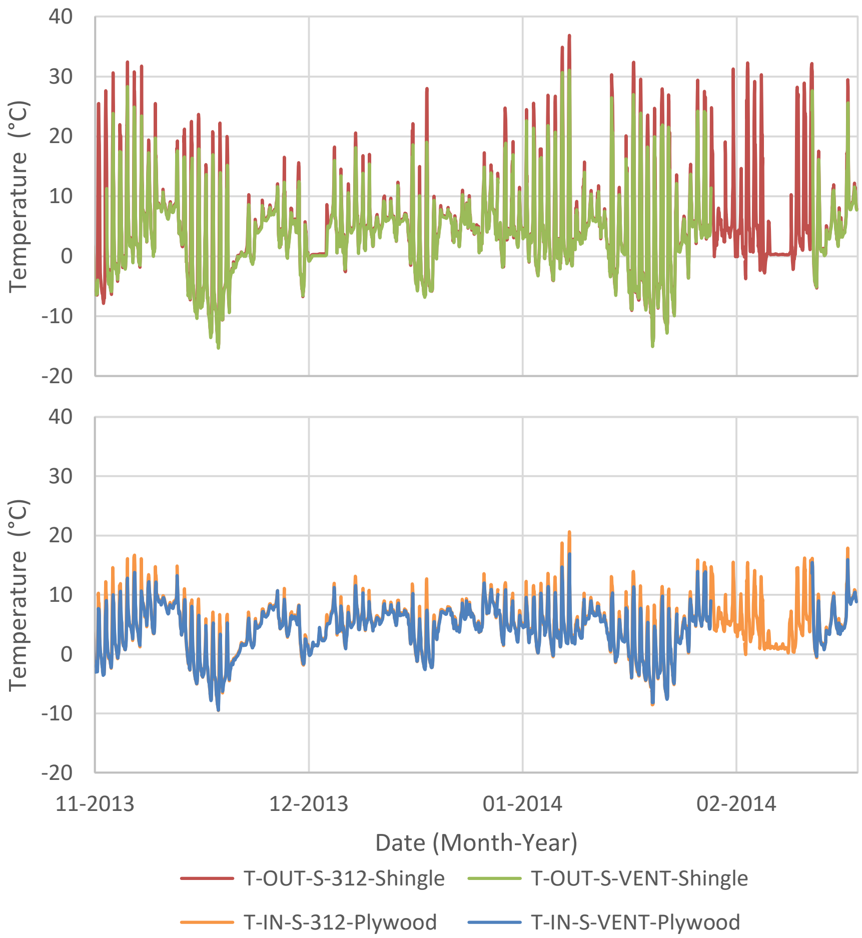


Figure 3.2– Shingle and Plywood Sheathing Temperatures for Vented (Vent) and Standard Roof (3:12 Pitch with Roofing Paper) – South Orientation

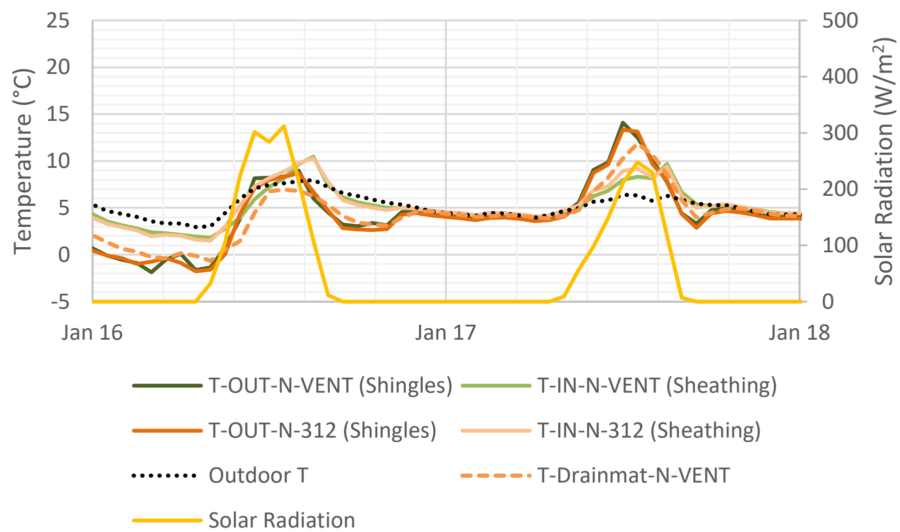


Figure 3.3– Plywood Sheathing Temperature on January 16 and 17, 2014 for Vented (Vent) and Standard Roof (3:12 Pitch with Roofing Paper) – North Orientation

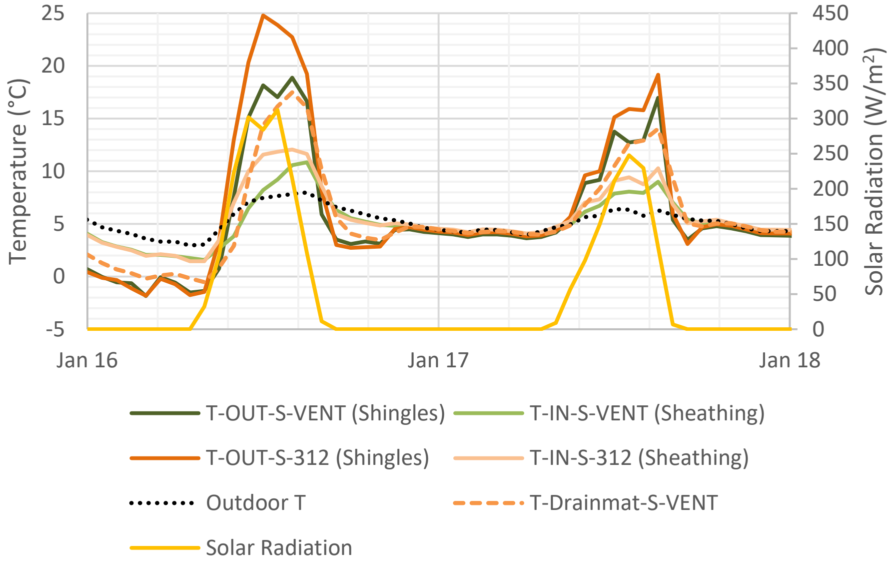


Figure 3.4– Plywood Sheathing Temperature on January 16 and 17, 2014 for Vented (Vent) and Standard Roof (3:12 Pitch with Roofing Paper) – South Orientation

The shingle and sheathing temperatures on both the North and South orientations increased when exposed to solar radiation for the 3:12 and the control roof; and in all cases this increase was larger on the South elevation. However, the increases in temperature were less for the vented roof assembly than for the traditional assembly. The lower peak shingle and sheathing temperatures experienced by the vented roof reduces the drying potential of this assembly as compared to the traditional roof.

The vented layer has little to no identifiable impact on the nighttime sheathing temperature depression, and consequently the reduced drying capacity with no change to the potential for wetting likely leads to increased moisture contents and increased risk of fungal growth for the vented roof as compared to the traditional 3:12 roof. To assess whether this is the case, moisture contents of the plywood sheathing for these roofs were examined and are provided in Figure 3.5 and Figure 3.6.

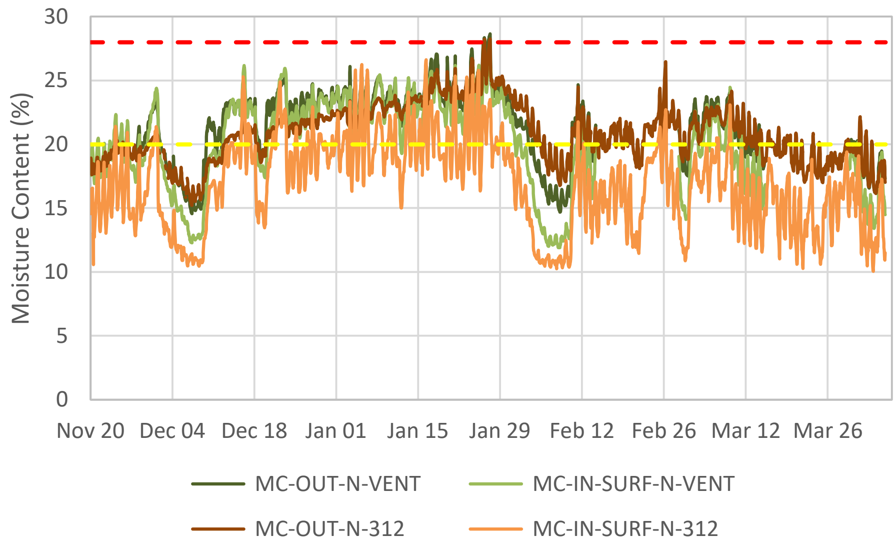


Figure 3.5– Plywood Sheathing Moisture Content for Vented (Vent) and Standard Roof (3:12 Pitch with Roofing Paper) – North Orientation

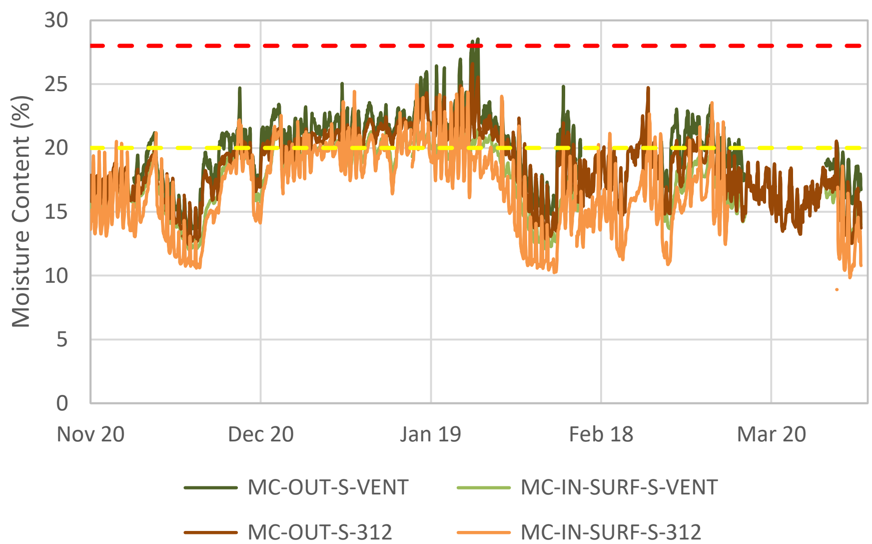


Figure 3.6– Plywood Sheathing Moisture Content for Vented (Vent) and Standard Roof (3:12 Pitch with Roofing Paper) – South Orientation

Figure 3.5 and Figure 3.6 illustrate that typically the roofs which experience less solar heat gain have higher monthly average moisture contents. The cause of this becomes apparent upon more detailed inspection which is provided in Figure 3.7 and Figure 3.8 for a period from January 16 to 18, 2014.

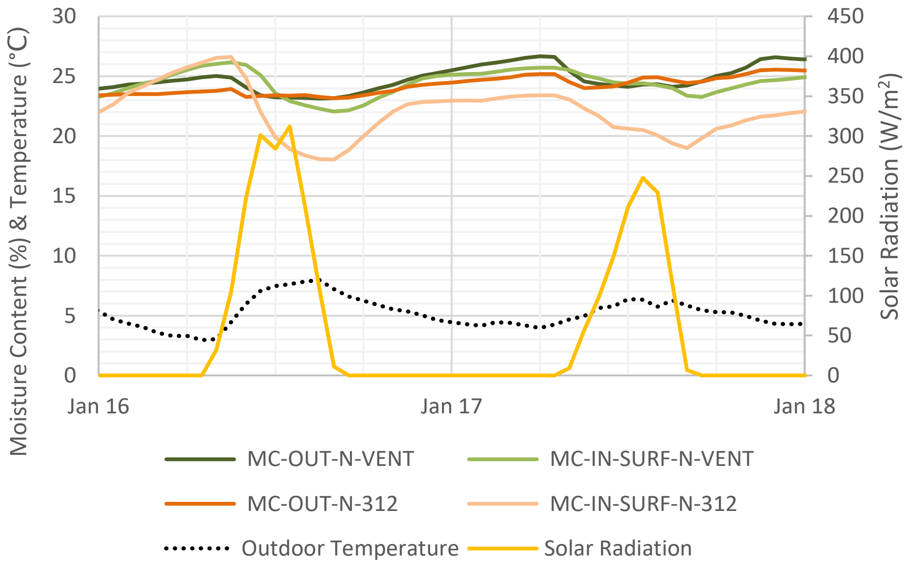


Figure 3.7– Plywood Sheathing Moisture Content for Vented (Vent) and Standard Roof (3:12 Pitch with Roofing Paper) – North Orientation

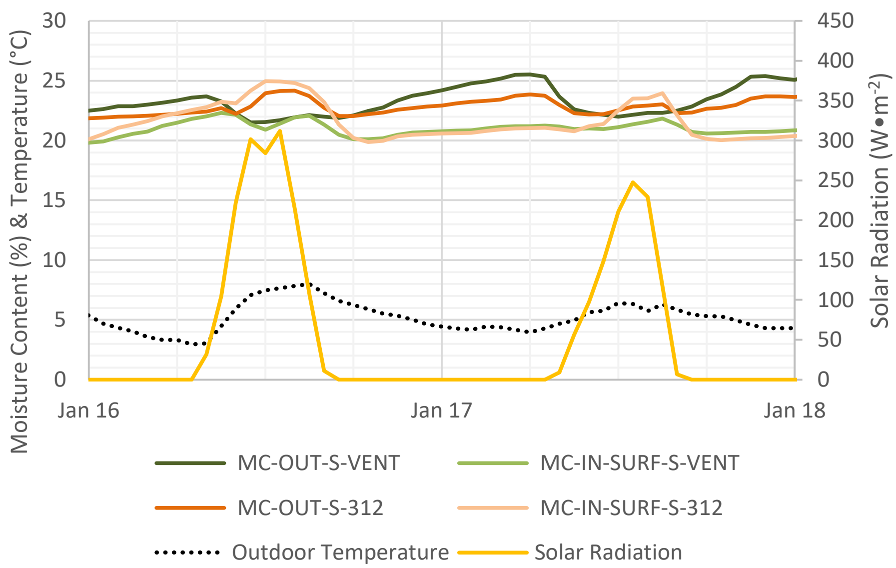


Figure 3.8– Plywood Sheathing Moisture Content for Vented (Vent) and Standard Roof (3:12 Pitch with Roofing Paper) – South Orientation

On the North orientation, both roof assemblies exhibited similar moisture content trends with an increase in ambient temperature and exposure to solar radiation resulting in drying of the sheathing, with more drying occurring in the 3:12 roof than in the control. The South orientations, however, have significantly different diurnal moisture content responses. The moisture content of the South orientation of the vented roof experiences drying of the outer layer of the sheathing, but since this layer cannot dry outward, the drying occurs inward and leads to a slight increase in the moisture content of the inner layer of the sheathing. The 3:12 roof on the other hand exhibited a noticeably different behaviour. Under solar heating, the moisture content of the sheathing first increased and then decreased. It is hypothesized that this is a result of moisture stored either between the shingle layers or between the shingles and the permeable underlay being driven inward by solar heating. Upon subsequent cooling, redistribution and evaporation occurs and the moisture content of both the inner and outer sheathing returns to the pre-heated conditions. Further investigation is required to confirm the moisture movement mechanisms.

To better show the differences in moisture performance, seasonal (winter and spring) average moisture contents and temperatures were calculated for day-time, night-time, and the full day. Separating the averages by diurnal variations helps identify the impacts of solar heat gain. The results are shown in Figure 3.9 and Figure 3.10. The dark coloured bars represent the sheathing surface moisture contents and the lighter coloured bars represent the interior sheathing temperatures, respectively.

These figures clearly illustrate that the vented roof experiences consistently colder sheathing temperatures during the day as well as higher moisture contents during both day and night. The vented layer has a particularly large effect on the moisture content of the North facing roof which experienced significantly elevated moisture contents compared to the South facing vented roof and both orientations of the unvented roof.

The night-time temperature of the vented assembly and the conventional assembly are nearly identical while the daytime temperatures of the 3:12 roof are higher than those of the vented roof. This suggests that the de-coupling capacity of a vented assembly is not sufficient to mitigate night-sky cooling; however, it does reduce the maximum temperatures reached during the day, thus decreasing drying capacity and likely leading to the higher moisture contents that were measured.

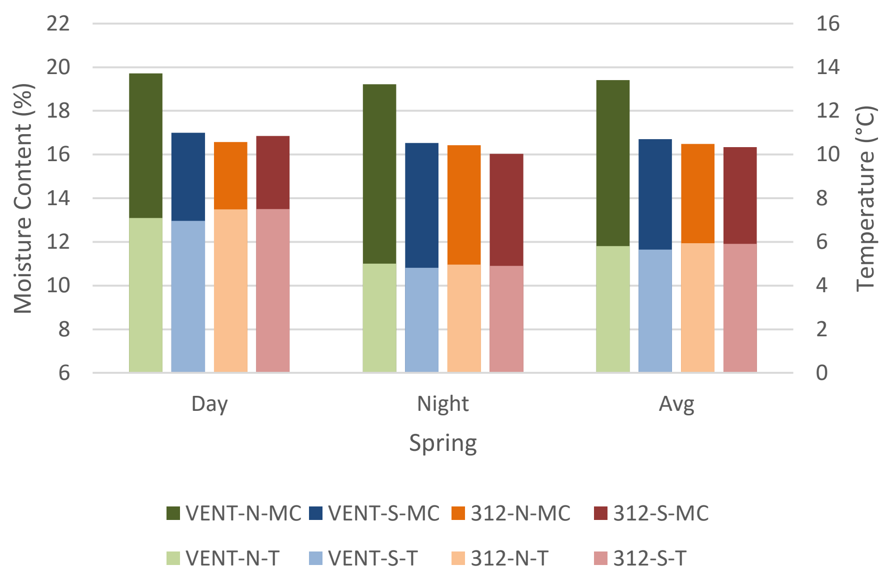


Figure 3.9– Spring (March 1, 2013 to April 30, 2013) Diurnal Moisture Content (SURF) and Temperature Averages for North and South Oriented Vented and Conventional Roof Assemblies

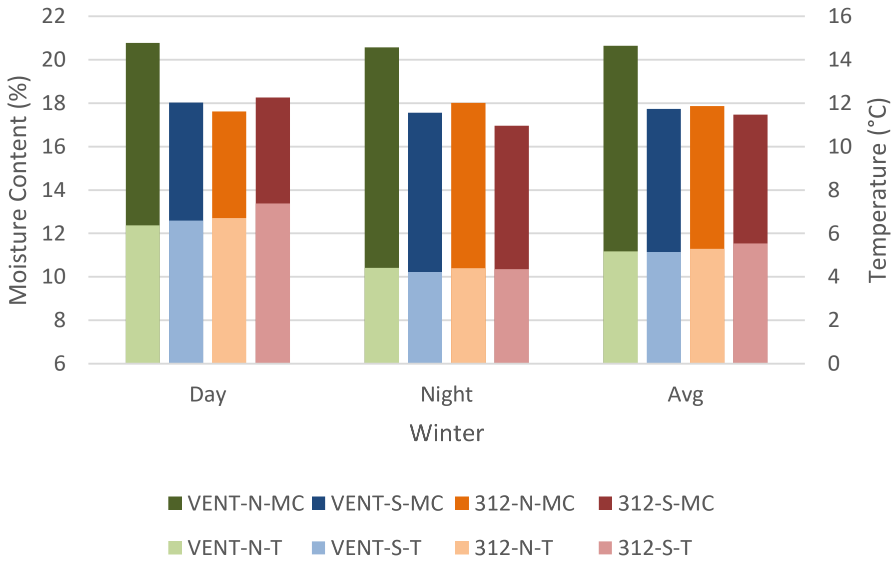


Figure 3.10– Winter (November 1, 2013 to January 31, 2014) Diurnal Moisture Content (SURF) and Temperature Averages for North and South Oriented Vented and Conventional Roof Assemblies

This is further corroborated by analysis of the number of hours of potential condensation on the sheathing as was provided earlier for the traditional roof constructions. Comparison of the number of hours that the plywood sheathing temperatures fall below the ambient air dew point temperature provides insight into the insulating capacity of the vented mat layer. The results are shown in Figure 3.11. The monitoring period was over a span of 96 days (≈2300 hours).

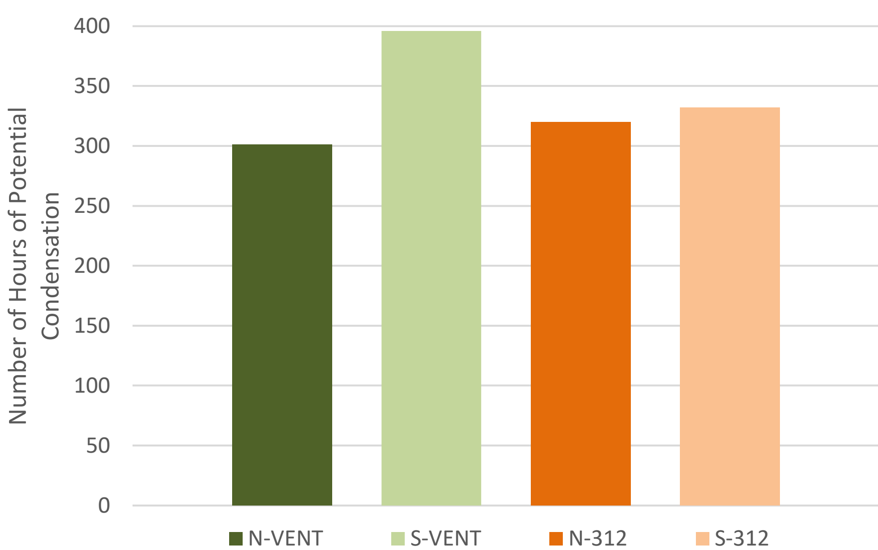


Figure 3.11– Number of Hours of Potential Condensation for Vented and Conventional Roof

This figure indicates that the vented and unvented roof assemblies experienced a similar number of hours of condensation (within 4% of the total number of hours), but that the South vented roof experienced slightly more hours of potential condensation than did the North roof. To further assess the cause of the difference between North and South the hourly potential condensation was plotted in Figure 3.12 for a two week period in January 2014.

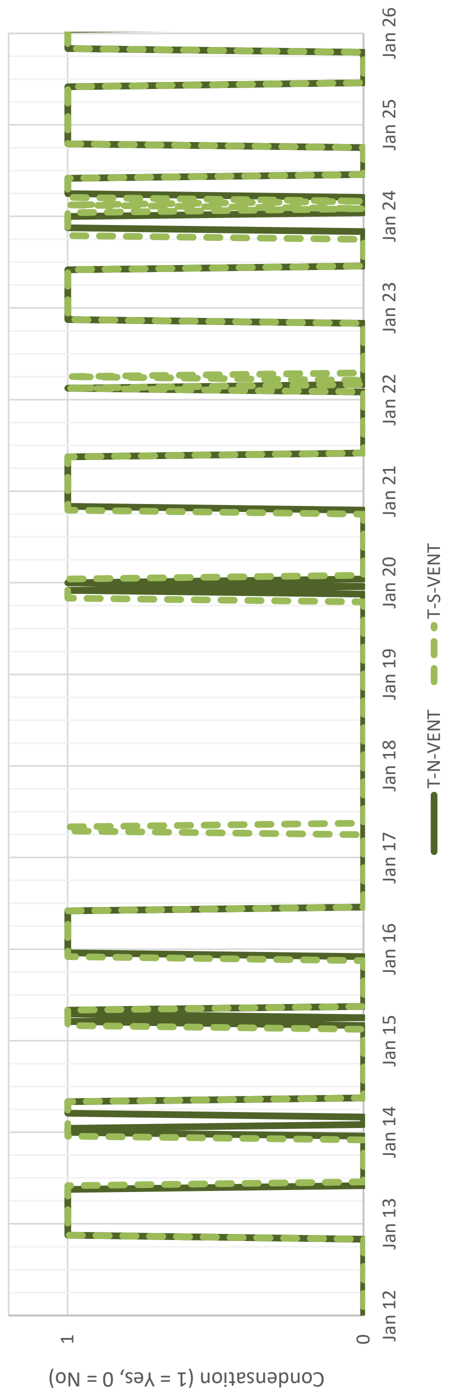


Figure 3.12 – Hours of Potential Condensation for the Vented Roof from January 12, 2014 to January 26, 2014

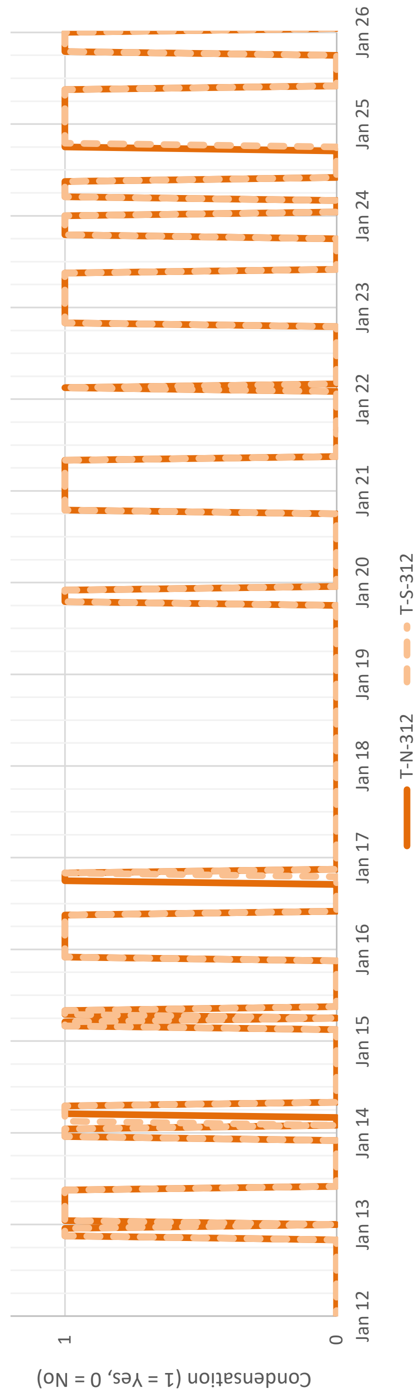


Figure 3.13 – Hours of Potential Condensation for the 3:12 Roof from January 12, 2014 to January 26, 2014

This figure shows that in some cases condensation is calculated for the South roof approximately one hour earlier than for the North roof; however, the cause of this difference is unknown since the 3:12 roof with no vent layer calculated hours of potential condensation (provided in Figure 3.13) shows nearly identical potential for condensation on both the North and South roofs.

In summary, comparison of the vented roof assembly with the standard roof assembly found that the vented layer significantly reduces the maximum temperature of the sheathing due to solar heat gains but has little to no effect on the minimum temperatures created by night sky cooling effects. Consequently, the addition of the vented layer reduces the drying capacity of the roof assembly while not affecting wetting of the assembly thereby increasing the moisture content of the sheathing as well as the risk of fungal growth.

3.2 Wood Preservative and Fungicide Surface Treatments

Surface mould growth can be modelled based on relative humidity and temperature, among other factors. Using Viitanen and Ojanen's (2007) mould index, a prediction of the mould growth for the 3:12 and the 6:12 sloped roofs on both the North and South orientations was undertaken using the measured temperature and relative humidity data. The definition of the mould growth indices are provided in Table 3.1.

TABLE 3.1– MOULD GROWTH INDEX (VIITANEN AND OJANEN, 2007)

INDEX	GROWTH RATE	DESCRIPTION
0	No Growth	Spores not activated
1	Small amounts of mould on surface (microscope)	Initial stages of growth
2	<10% coverage of mould on surface (microscope)	Further limited growth
3	10%-30% coverage of mould on surface (visual)	New spores produced
4	30%-70% coverage of mould on surface (visual)	Moderate growth
5	>70% coverage of mould on surface (visual)	Plenty of growth
6	Very heavy and tight growth	Coverage around 100%

The model assumes that a certain amount of germination time is required prior to macroscopic mould growth. This is accounted for in the 0 to 1 mould index, whereby only microscopic observations could confirm the presence of mould. Subsequent indices, from 2 to 5, cover the range of mould growth from less than 10% of the surface area, to near complete mycelia matting. It should be noted that based on environmental conditions, a maximum degree of mould can be supported; the calculations indicate a maximum mould index of approximately 5. The results of the predicted mould growth are shown Figure 3.14

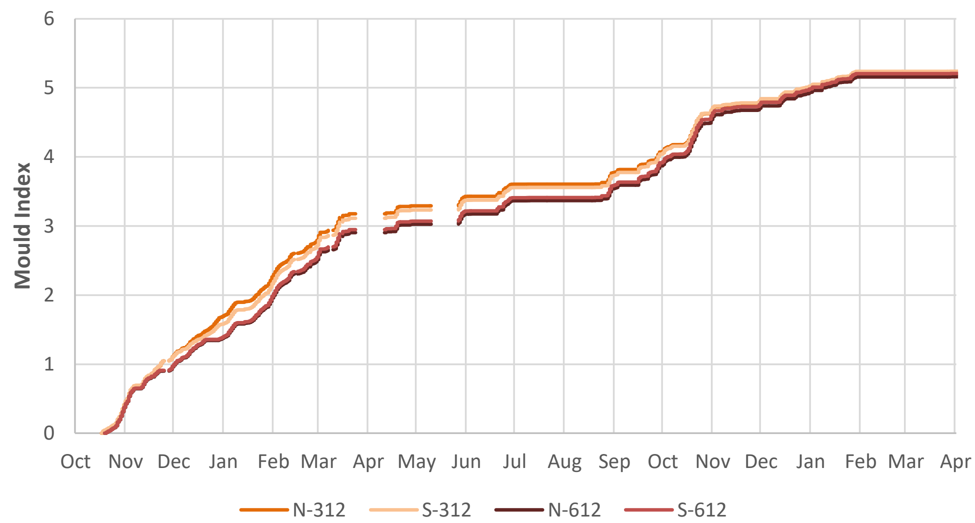
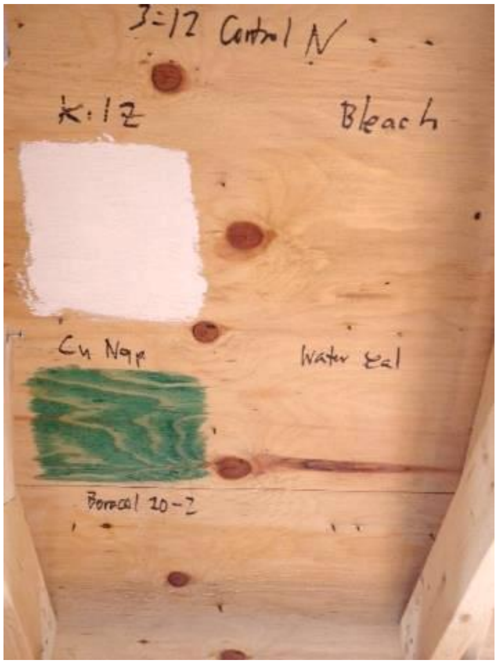
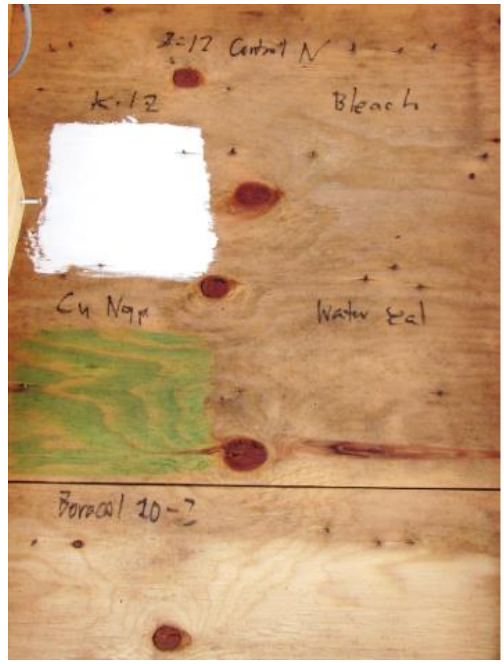


Figure 3.14– Mould Growth Index for 312 and 612 Roof Pitch for North and South Orientation

The results of the mould modelling suggest that the 3:12 roof pitch would exhibit slightly faster occurrence of mould compared to the 6:12 roof pitches. Similarly, mould growth was calculated to occur faster on the North orientation than on the South. Despite the predicted faster initial mould growth on the lower sloped and North facing roofs, after a period of two years, mould growth is predicted to reach its maximum on all of the roofs based on the substrate and the environmental conditions. It should be noted that mould growth reduction from high temperatures (>40˚C) or dry periods (<80% RH), which may cause cessation of mould growth, or desiccation, was not included as part of this analysis.

The impact of the wood preservative and fungicide surface treatments on mould growth were analysed visually and images of the underside of the sheathing showing the treatments when applied and after the initial exposure of 12 to 18 months are provided in the following tables.

<table>
<tr><th colspan="3">SURFACE TREATMENT VISUAL COMPARISON – CONTROL ROOF</th></tr>
<tr><th colspan="3">CONTROL ROOF APPLICATION ROUND 1</th></tr>
<tr><td></td><td>2012/10/15: When Applied</td><td>2014/04/07: 1.5 Years Later</td></tr>
<tr><td>North</td><td>
</td><td>
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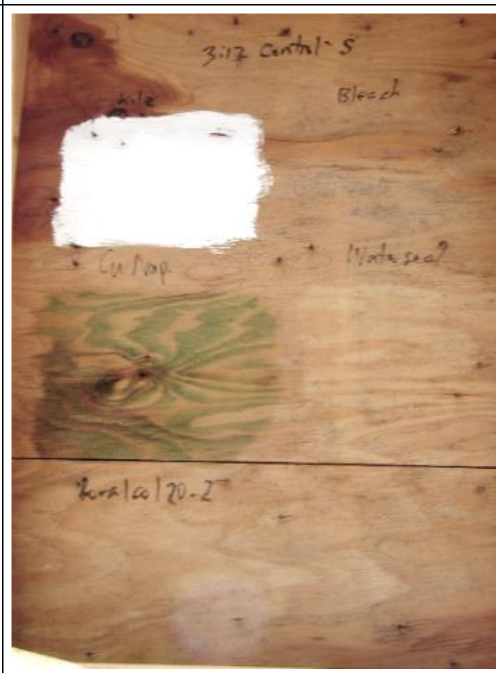
<tr><td>South</td><td>
</td><td>
</td></tr>
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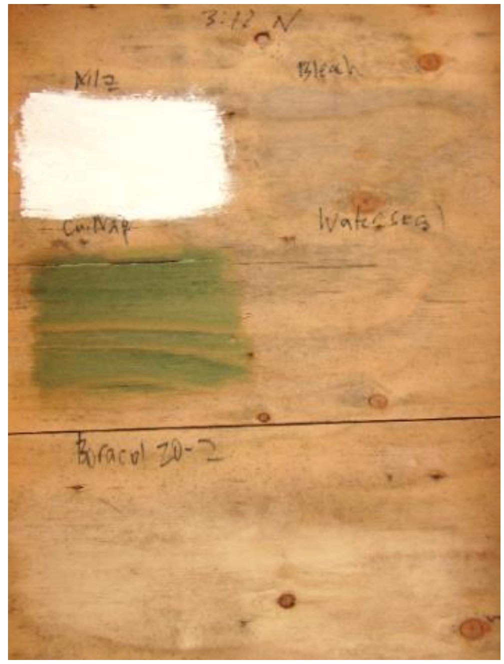
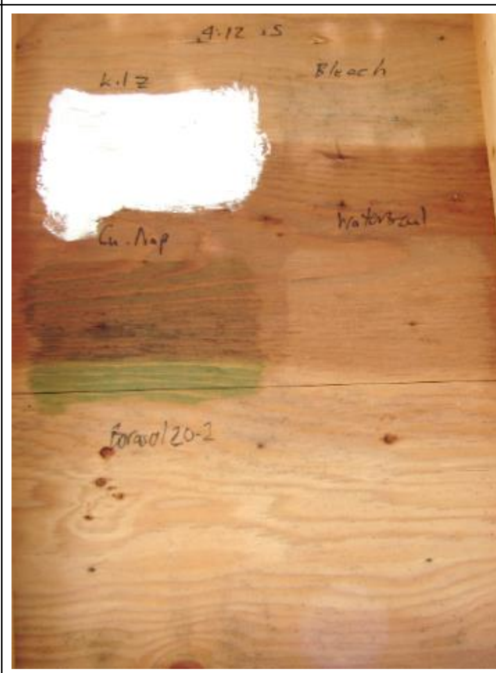
CONTROL ROOF APPLICATION ROUND 2		
	2013/04/11: When Applied (After first Winter)	2014/04/07: 1 Year Later
North		
South		

<table>
<tr><th colspan="3">SURFACE TREATMENT VISUAL COMPARISON – 3:12 ROOF</th></tr>
<tr><th colspan="3">3:12 ROOF APPLICATION ROUND 1</th></tr>
<tr><td></td><td>2012/10/15: When Applied</td><td>2014/04/07: 1.5 Years Later</td></tr>
<tr><td>North</td><td></td><td></td></tr>
<tr><td>South</td><td></td><td></td></tr>
</table>

3:12 ROOF APPLICATION ROUND 2

	2013/04/11: When Applied (After 1 Winter)	2014/04/07: 1 Year Later
North		
South		

<table>
<tr><th colspan="3">SURFACE TREATMENT VISUAL COMPARISON – 4:12 ROOF</th></tr>
<tr><th colspan="3">4:12 ROOF APPLICATINO ROUND 1</th></tr>
<tr><td></td><td>2012/10/15: When Applied</td><td>2014/04/07: 1.5 Years Later</td></tr>
<tr><td>North</td><td>
</td><td>
</td></tr>
<tr><td>South</td><td>
</td><td>
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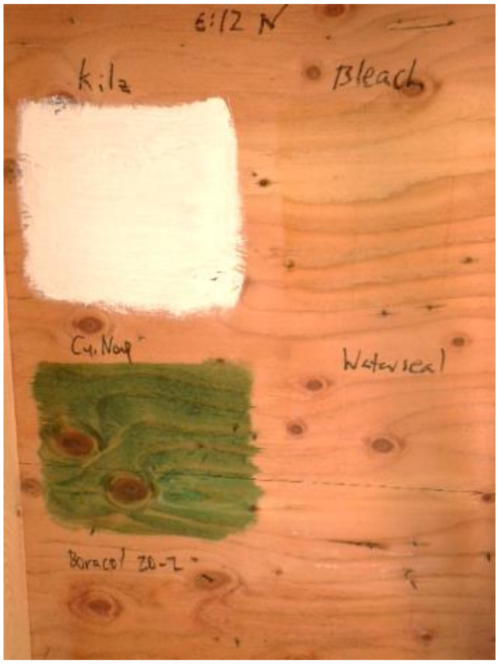
<table>
<tr><th colspan="3">4:12 ROOF APPLICATION ROUND 2</th></tr>
<tr><td rowspan="2">North</td><td>2013/04/11: When Applied
(After first Winter)</td><td>2014/04/07: 1 Year Later</td></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td>South</td><td>
</td><td>
</td></tr>
</table>

<table>
<tr><th colspan="3">SURFACE TREATMENT VISUAL COMPARISON – 6:12 ROOF</th></tr>
<tr><th colspan="3">6:12 ROOF APPLICATION ROUND 1</th></tr>
<tr><td></td><td>2012/10/15: When Applied</td><td>2014/04/07: 1.5 Years Later</td></tr>
<tr><td>North</td><td>
</td><td>
</td></tr>
<tr><td>South</td><td>
</td><td>
</td></tr>
</table>

6:12 ROOF APPLICATION ROUND 2		
	2013/04/11: When Applied (After first Winter)	2014/04/07: 1 Year Later
North		
South		

To summarize the efficacy of the surface treatments, a visual rating system was developed and applied to each roof hut orientation. The results from the initial assessment after the first 12 to 18 months (based on product application, see above) are shown in Table 3.3 below

TABLE 3.2 – VISUAL ASSESSMENT OF SURFACE TREATMENT EFFICACY AT 2014/04/07														
Test Roof	**Surface Treatments (North left, South right)**													
	Sansin Boracol® 20-2		Copper Naphthenate		Bleach		Thompsons WaterSeal ®		Kilz® Paint		Zinc Naphthenate		Sansin Boracol® 20-2BD	
Direction	N	S	N	S	N	S	N	S	N	S	N	S	N	S
Control	Moderate	Moderate	Pristine	Moderate	Significant	Significant	Significant	Significant	Pristine	Pristine	Moderate	Moderate	Pristine	Pristine
3:12	Significant	Pristine	Moderate	Pristine	Significant	Pristine	Significant	Pristine	Pristine	Pristine	Moderate	Moderate	Pristine	Pristine
4:12	Significant	Pristine	Pristine	Moderate	Significant	Significant	Significant	Moderate	Pristine	Pristine	Moderate	Pristine	Pristine	Moderate
6:12	Moderate	Pristine	Pristine	Pristine	Moderate	Pristine	Significant	Significant	Pristine	Pristine	Pristine	Pristine	Pristine	Pristine

VISUAL ASSESSMENT SCALE

- Pristine or very light fungal growth
- Moderate fungal growth
- Significant fungal growth

The North orientation exhibited the greatest degree of fungal growth on all three roof pitches, with the 6:12 roof showing the least amount of growth. The South facing slopes were in generally better condition, with the 6:12 pitch similarly showing the least fungal growth. This is somewhat in contrast to the previously stated findings of more hours of condensation and a larger temperature depression due to night sky cooling for the 6:12 roofs; however, it is consistent with the findings with respect to temperatures due to solar heat gains.

In regard to the efficacy of the fungal treatments, in general, the bleach and Thompson's WaterSeal® were inadequate in preventing mould growth in the initial exposure period. In some cases, it appears as if the antifungal properties of bleach have primed the surface for a new wave of fungal colonization by eliminating the established fungi, resulting in more severe fungal growth than the adjacent areas. The Boracol 20-2BD, Kilz® Paint, Copper Naphthenate and Zinc Naphthenate seemed to provide some resistance to fungal growth at this early stage. It is also apparent that products with mouldicides (e.g. Boracol 20-2BD and Kilz® Paint) perform better than wood preservatives primarily designed to prevent decay (Copper and Zinc Naphthenate).

A follow-up review was completed in January 2018 for the 6:12, 4:12, and 3:12 roof, to assess the longer-term efficacy of the treatments in minimizing visible fungal growth. The control roof was dismantled by this time. In most cases, the trends found in the initial early stage assessment also appeared in the follow-up long term review.

The results of the follow up visual review are shown in Table 3.3, and a summary of the worst-case observed visible fungal growth for the entire test period are shown in Table 3.4.

TABLE 3.3 – VISUAL ASSESSMENT OF SURFACE TREATMENT EFFICACY AT 2018/01/22

Test Roof	Surface Treatments													
	Sansin Boracol® 20-2		Copper Naphthenate		Bleach		Thompsons WaterSeal ®		Kilz® Paint		Zinc Naphthenate		Sansin Boracol® 20-2BD	
Direction	N	S	N	S	N	S	N	S	N	S	N	S	N	S
Control*	Orange	Orange	Green	Orange	Red	Red	Red	Red	Green	Green	Orange	Orange	Green	Green
3:12	Green	Red	Orange	Green	Red	Red	Green	Orange	Green	Green	Orange	Red	Green	Orange
4:12	Green	Green	Orange	Green	Orange	Red	Green	Orange	Green	Green	Green	Orange	Green	Green
6:12	Orange	Red	Orange	Green	Orange	Red	Red	Green	Green	Green	Orange	Orange	Green	Orange

VISUAL ASSESSMENT SCALE

- Green: Pristine or very light fungal growth
- Orange: Moderate fungal growth
- Red: Significant fungal growth

*Does not include results beyond 2014/04/07

TABLE 3.4 – VISUAL ASSESSMENT OF SURFACE TREATMENT EFFICACY – ALL TIME														
Test Roof	**Surface Treatments**													
	Sansin Boracol® 20-2		Copper Naphthenate		Bleach		Thompsons WaterSeal ®		Kilz® Paint		Zinc Naphthenate		Sansin Boracol® 20-2BD	
Direction	N	S	N	S	N	S	N	S	N	S	N	S	N	S
Control*	🟧	🟧	🟩	🟧	🟥	🟥	🟥	🟥	🟩	🟩	🟧	🟧	🟩	🟩
3:12	🟥	🟥	🟧	🟩	🟥	🟥	🟥	🟧	🟩	🟩	🟧	🟥	🟩	🟧
4:12	🟥	🟩	🟧	🟧	🟥	🟥	🟥	🟧	🟩	🟩	🟧	🟧	🟩	🟧
6:12	🟧	🟥	🟧	🟩	🟧	🟥	🟥	🟥	🟩	🟩	🟧	🟧	🟩	🟧

VISUAL ASSESSMENT SCALE

- 🟩 Pristine or very light fungal growth
- 🟧 Moderate fungal growth
- 🟥 Significant fungal growth

*Does not include results beyond 2014/04/07

As found in the initial exposure period, the only surface treatment with no visible fungal growth was the Kilz Paint, even after over five years of exposure. This finding coincides with the results of additional laboratory testing completed by FPInnovations (see References section).

Interestingly, visible fungal growth has not occurred to any significance on most heartwood sections of the plywood to date. This may be a result of the decreased moisture content (due to the presence of extractives) or the natural fungal resistance of heartwood. Further investigation is required.

The fungal growth on the roof hut sheathing was tested and determined to be primarily *Cladosporium* genus in all locations. Mould growth on the underside of the plywood roof sheathing is technically outside the air barrier, and consequently, in a building with an airtight ceiling assembly, the exposure of occupants to the fungal growth would likely be minimal. While the actual health risks associated with mould on the roof sheathing are not well established, a method to prevent this mould growth is desired to address perceived health risks and associated impacts on property value.

4 Recommendations and Conclusions

The findings of this study clearly demonstrate that sloped wood-frame attic roof assemblies experience wetting in the Lower Mainland of BC despite the elimination of typical moisture sources including the leakage of interior air into the attic, and that this cannot be prevented by ventilation alone. For the test roofs, this wetting combined with seasonal fluctuation in the sheathing moisture content created by changes in ambient conditions led to sustained periods in which the sheathing moisture content was sufficient to both initiate and sustain fungal growth.

The moisture content measurements indicate that the moisture content of the plywood is most closely related to outdoor climatic conditions, notably exterior ambient temperature and relative humidity, with the moisture contents of all four roof assemblies surpassing 20% in the winter, and drying out in the summer. While the largest factor affecting sheathing moisture content was the ambient conditions, in many cases the sheathing moisture content was measured to be significantly above or below the equilibrium moisture content indicating that other wetting and drying mechanisms were acting on the sheathing. These mechanisms were determined to be primarily: condensation on the underside of the sheathing due to night sky cooling depressing the sheathing temperature below the dew point of the ambient air, and solar heating of the roof surface increasing the sheathing temperature and facilitating drying.

Typically the North roof orientations experienced higher moisture contents than did the South orientations, for all of the different roof slopes, and only minor differences in the moisture contents based on roof slope was observed. This is despite the finding that the 6:12 sloped test roof experienced more hours of potential condensation than did the 3:12 and 4:12 roofs. Visual observations confirmed fungal growth on the plywood sheathing of the roof huts for all slopes and orientations, with more mould growth observed on the lower sloped roofs and on the North orientations which is consistent with the increased drying of these roofs due to increased daytime temperatures caused by solar heat gains.

The relative performance of the roof with impermeable and permeable underlayments was also assessed as part of this study. The sheathing in the roofs with the impermeable underlay were measured to have higher moisture contents than the roofs with the impermeable underlay, likely as a result of restricted outward drying. While it was hypothesized that the impermeable membrane would provide improved resistance to water ingress, no apparent water penetration through the shingles was observed. Further testing of aged or organic covered shingles should be performed to assess in-situ performance of compromised systems.

These findings are of concern to the construction industry as sloped wood-frame attic roof assemblies are the most prevalent type of roof assembly in low-rise wood-frame buildings, and the cost to upgrade them to an exterior insulated or unvented attic is often prohibitive, or in some cases may not address all of the design issues. Furthermore, the ubiquitous use of these roof assemblies makes it highly unlikely that they will stop being used in the marketplace. Consequently, while the actual health risks associated with mould on the roof sheathing are not well established, a method to prevent this mould growth is desired to address perceived health risks and associated impacts on property value.

One of the potential mitigation methods that was investigated was the installation of a vented layer between the roof underlay and the shingles. This underlay was found to decrease the drying potential of the roof by decreasing the daytime temperatures due to solar heat gain more than it decreased the wetting of the sheathing by reducing night sky radiation effects. Consequently, top venting of the sloped wood-frame attic roof assemblies does not likely provide an appropriate mitigation technique to the problem of fungal growth on the roof sheathing.

Another potential mitigation technique that was investigated was the application of wood preservative and fungicide treatments to the underside of the roof sheathing. The bleach and surface water-seal methods were not found to significantly mitigate mould growth and, in some cases, seem to exacerbate it. The capacity of the other surface treatments to mitigate mould growth appears promising, but further evaluation is required to ascertain long-term viability as well as the potential for use in remedial applications.

Overall the problem of fungal growth on the underside of sloped wood-frame roof sheathing is complex with a number of factors impacting wetting and drying, and so far no reliable cost-effective mitigation measures have been proven. Given the ubiquitous nature of these roofs, the identification, testing, and field validation of a cost effective mitigation measure is important to the continued application of these roof assemblies, unless public perception of the perceived health risks can be altered.

5 Further Research

The results of this research demonstrate that fungal growth occurs on the underside of sloped wood-frame roof sheathing even in the absence of water ingress through the shingles, and of air leakage from the interior and ducts. Furthermore, this growth cannot be prevented by ventilation alone and increasing ventilation could have a negative effect in many attics. Given that no mitigation measure has been proven for this type of assembly, a number of potential areas of future research have been identified. These include:

→ Assessment of mitigation strategies based on the use of materials which are resistant to fungal growth. This strategy may consist of either inorganic sheathing materials, or could potentially be achieved through the application of a surface preservative treatment.

→ Assessment of mitigation strategies based on reducing the effects of night-sky cooling while attempting to retain solar radiative drying such that the sheathing moisture content is maintained below levels which can support fungal growth. These strategies would rely on the successful balancing of drying and wetting mechanisms and could potentially include the addition of substantial insulation outboard of the sheathing or the use of low emissivity but highly solar absorptive roofing materials. The latter would experience less cooling due to night sky radiation while maintaining drying due to solar heat gains and could be similar to materials currently used for solar thermal collectors.

→ Further assessment of the impacts of roofing underlay permeance and water penetration resistance including in assemblies with weathered shingles and/or penetrations where there is a higher likelihood of moisture ingress.

→ Long-term evaluation of surface treatments such as fungicides to determine their efficacy and the potential need for reapplication (see Phase 2 report).

→ Evaluation of the moisture storage capacity of weathered shingles.

Note that at the time of publication of this report, additional laboratory testing has been completed by FPInnovations, and follow-up field testing was completed by RDH in Phase 2 of this study. See the Reference section for more information.

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Appendix A

Monitoring Data Plots

Additional graphs are provided in this appendix to supplement those provided in the main body of the report. In some cases graphs are repeated here from the main body of the report for completeness.

Weather Data

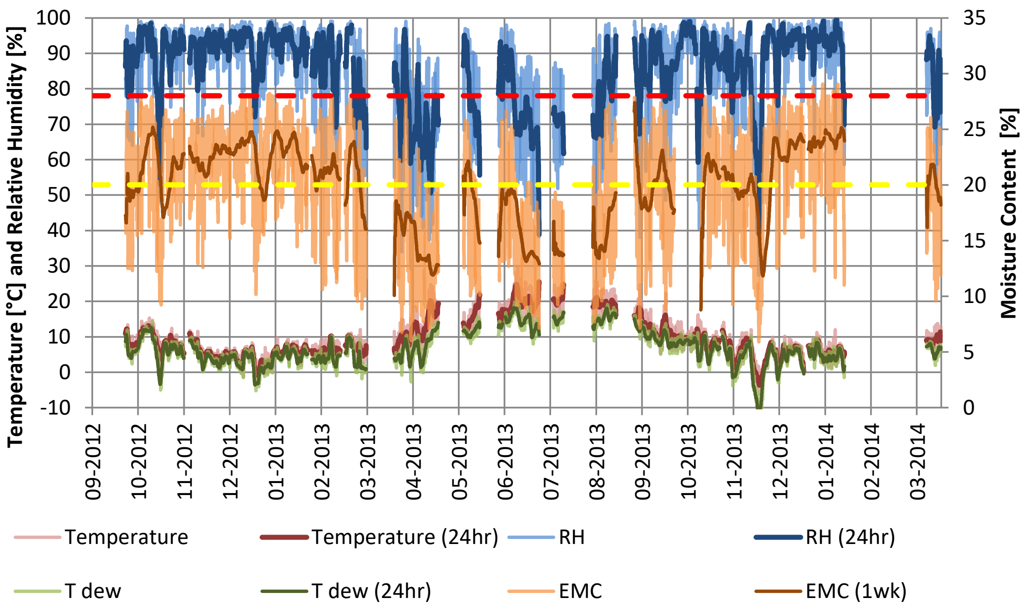

Figure 1- Temperature, Relative Humidity, and Equivalent Moisture Content

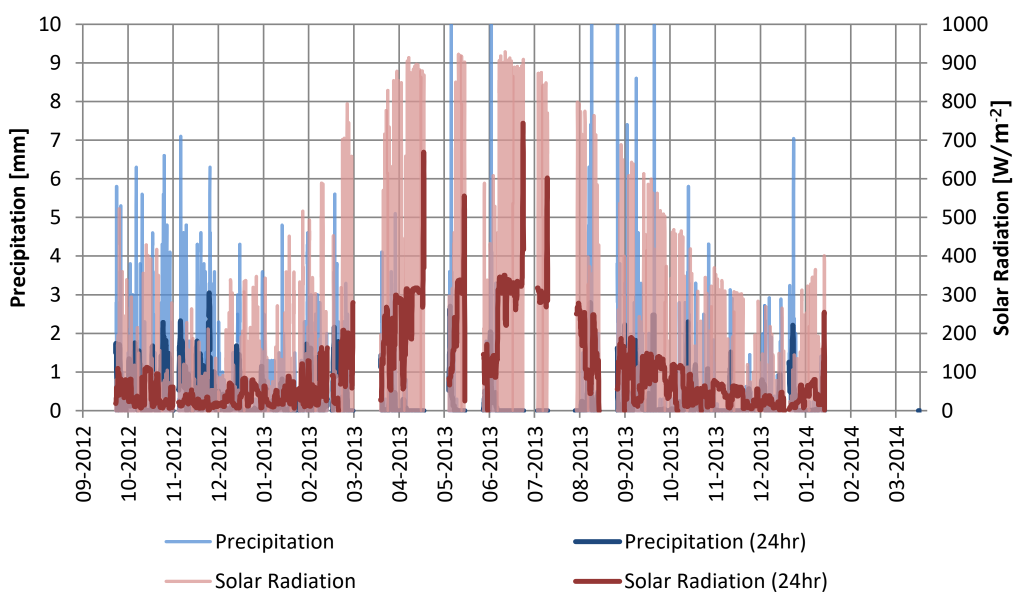

Figure 2 – Precipitation and Solar Radiation

Moisture Content– Seasonal Averages

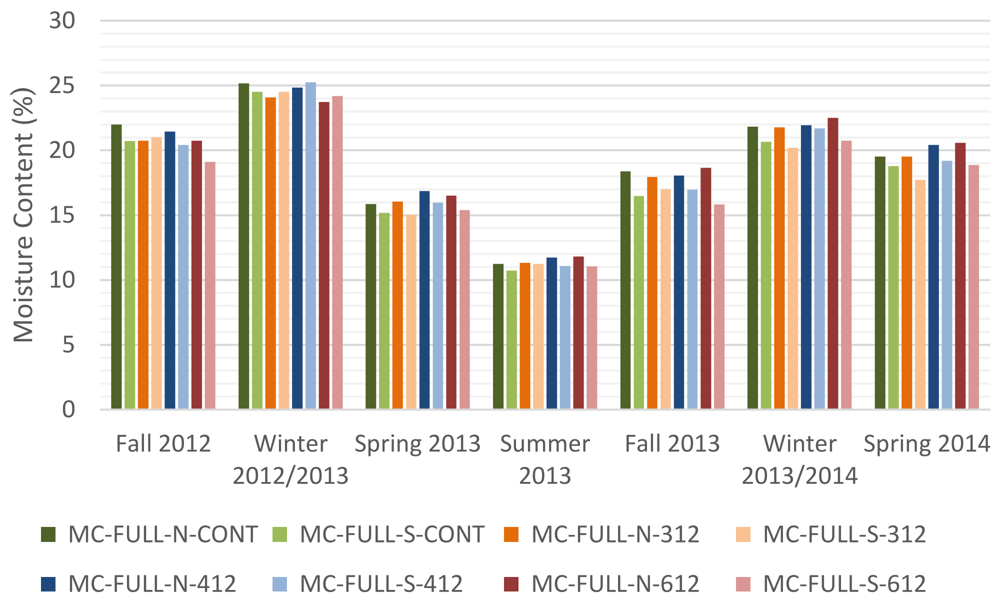

Figure 3 – Seasonal Average Sheathing Moisture Content for North and South Elevations–Full Depth

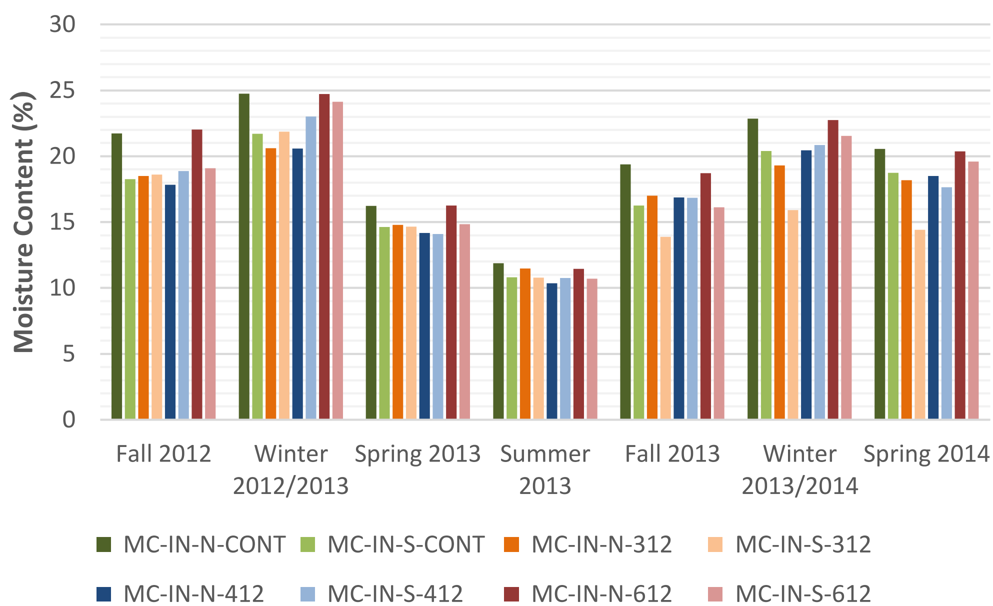

Figure 4 – Seasonal Average Sheathing Moisture Content for North and South Elevations–Inner 1/8" Depth

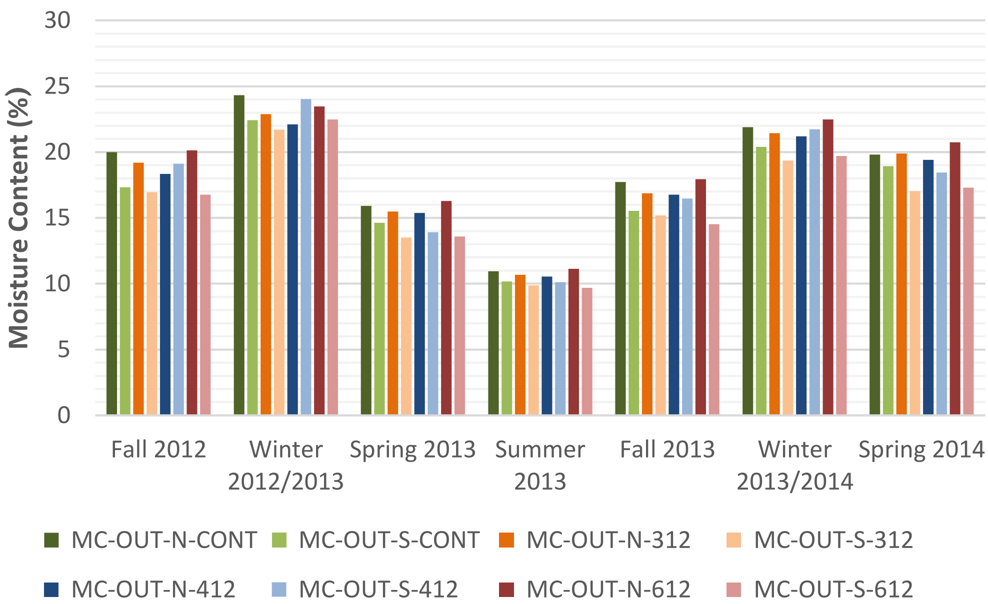

Figure 5 – Seasonal Average Sheathing Moisture Content for North and South Elevations–Outer 1/8" Depth

Moisture Content

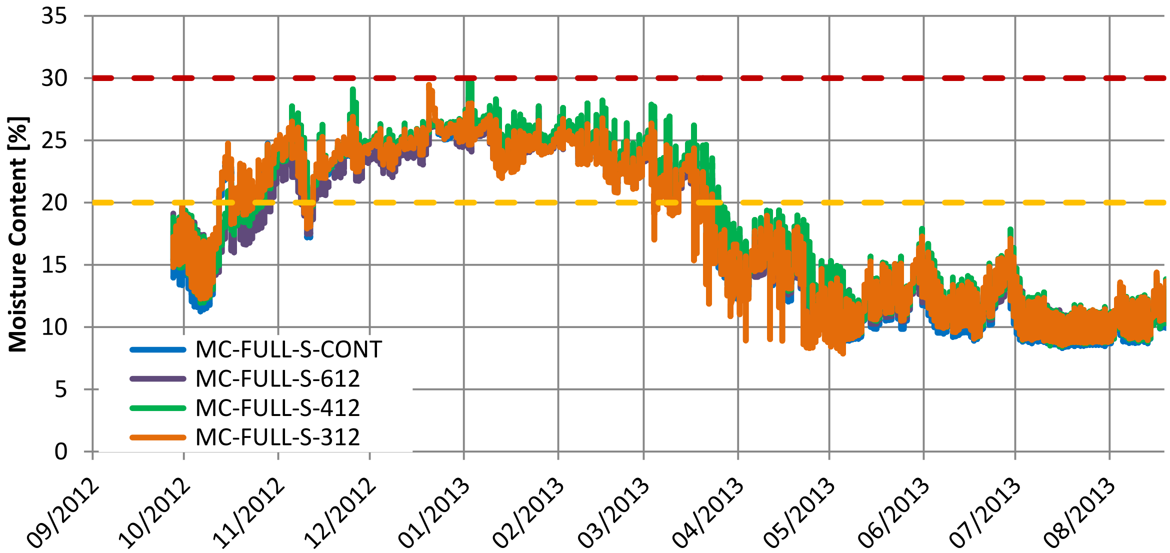

Figure 6 – Moisture Content, Full Depth, South Roof, for CONT, 6:12, 4:12, and 3:12

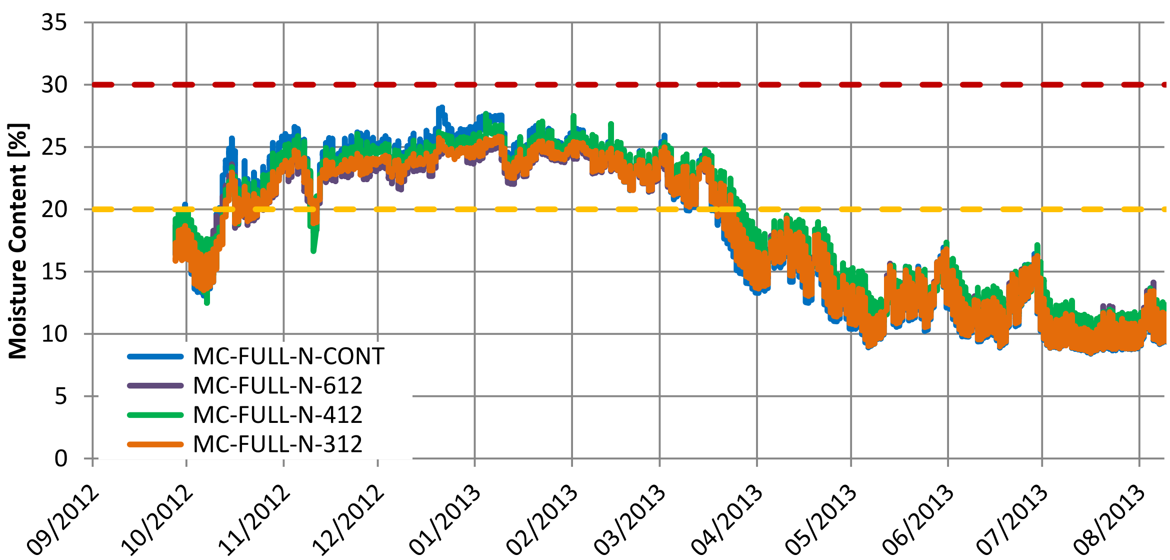

Figure 7 – Moisture Content, Full Depth, North Roof, for CONT, 6:12, 4:12, and 3:12

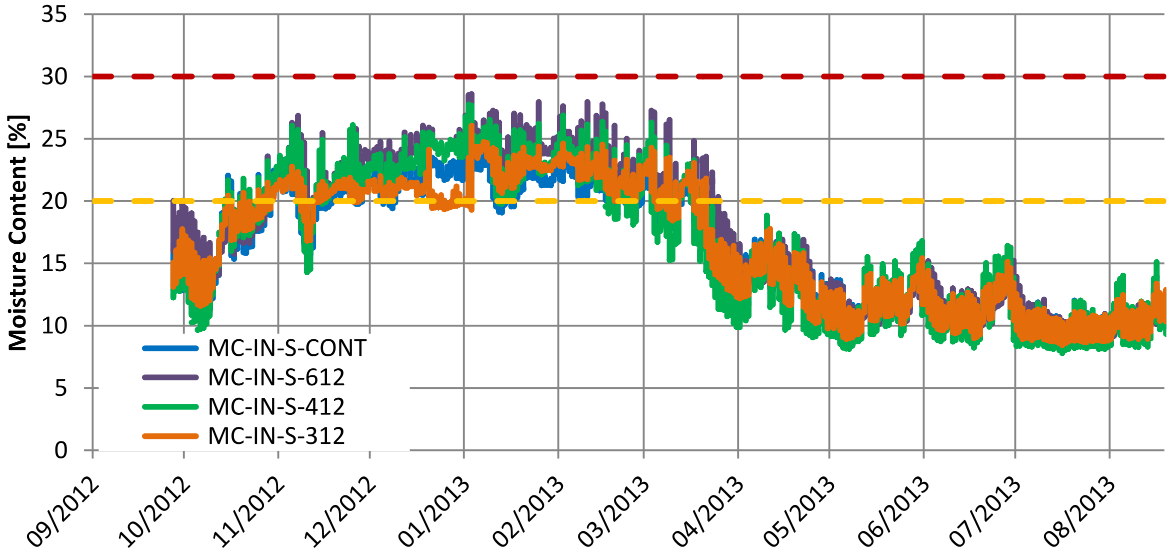

Figure 8 – Moisture Content, Inner 1/8" Depth, South Roof, for CONT, 6:12, 4:12, and 3:12

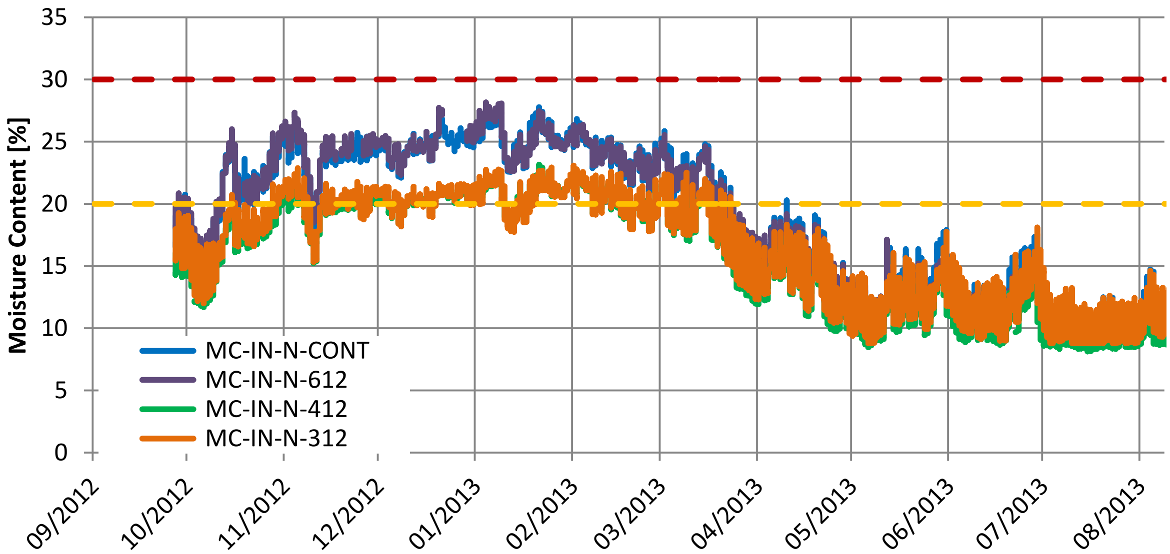

Figure 9 – Moisture Content, Inner 1/8", North Roof, for CONT, 6:12, 4:12, and 3:12

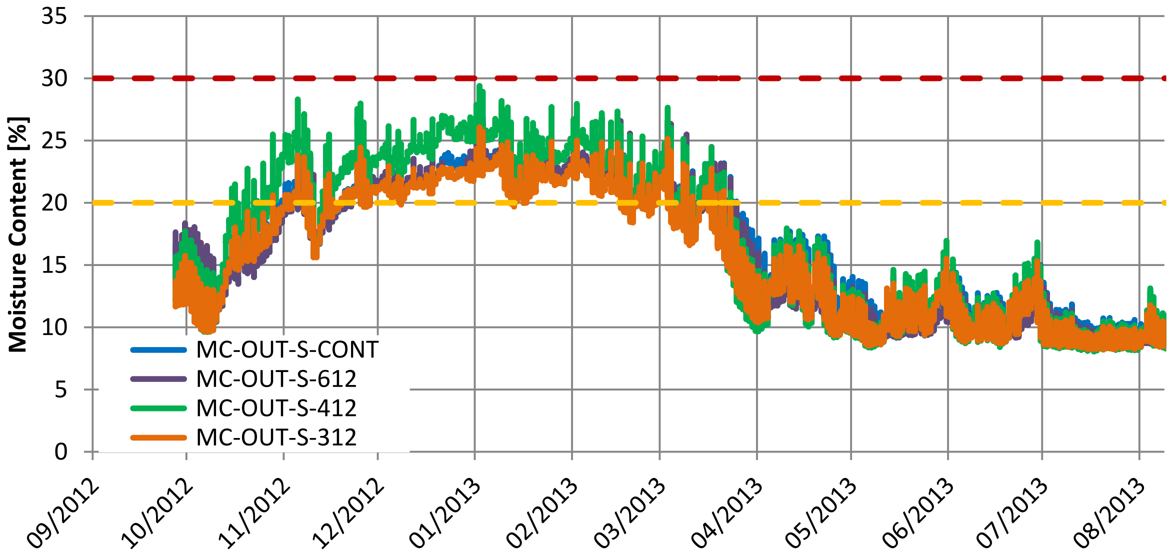

Figure 10 – Moisture Content, Outer 1/8", South Roof, for CONT, 6:12, 4:12, and 3:12

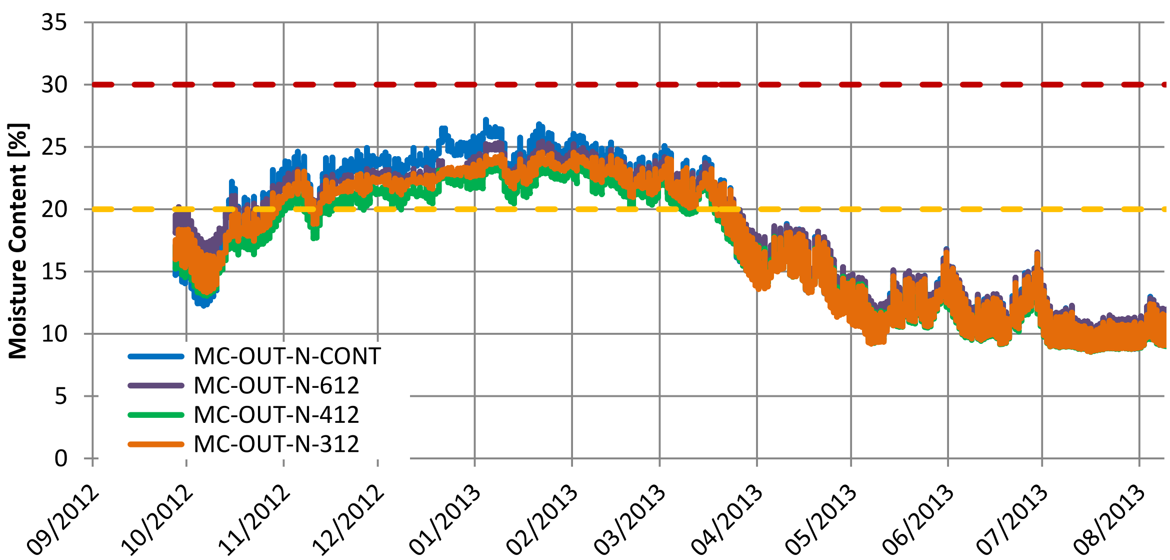

Figure 11 – Moisture Content, Outer 1/8", North Roof, for CONT, 6:12, 4:12, and 3:12

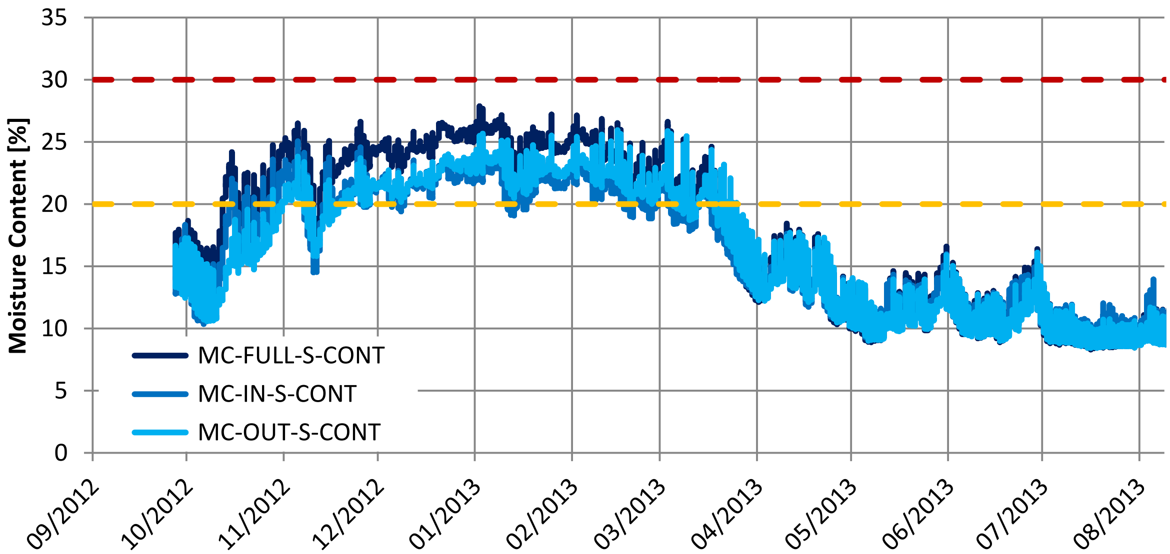

Figure 12 – Moisture Content, South Control Roof, Full, Inner, and Outer Sensors

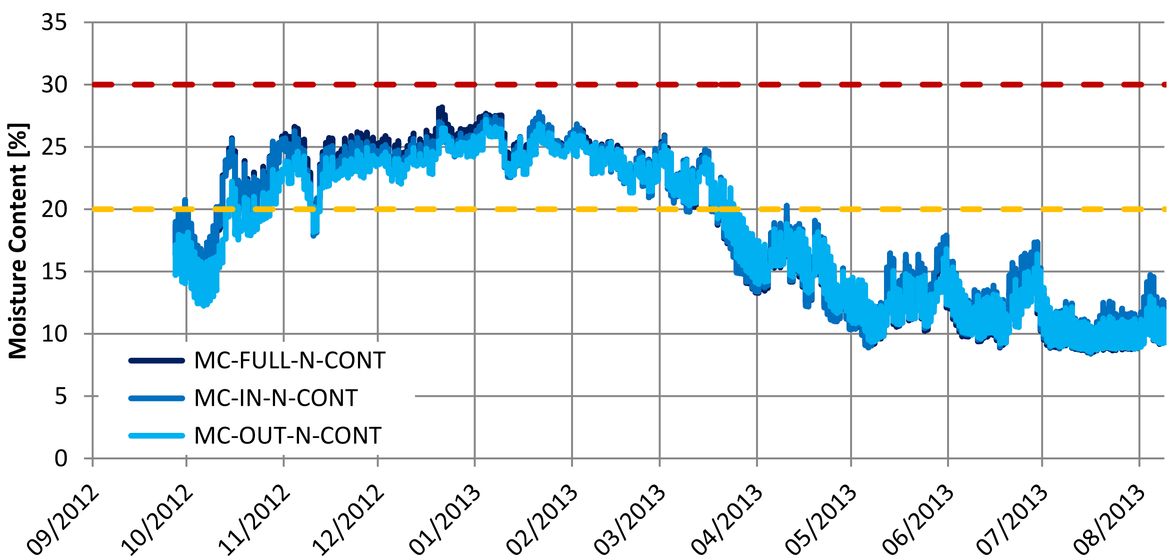

Figure 13 – Moisture Content, North Control Roof, Full, Inner, and Outer Sensors

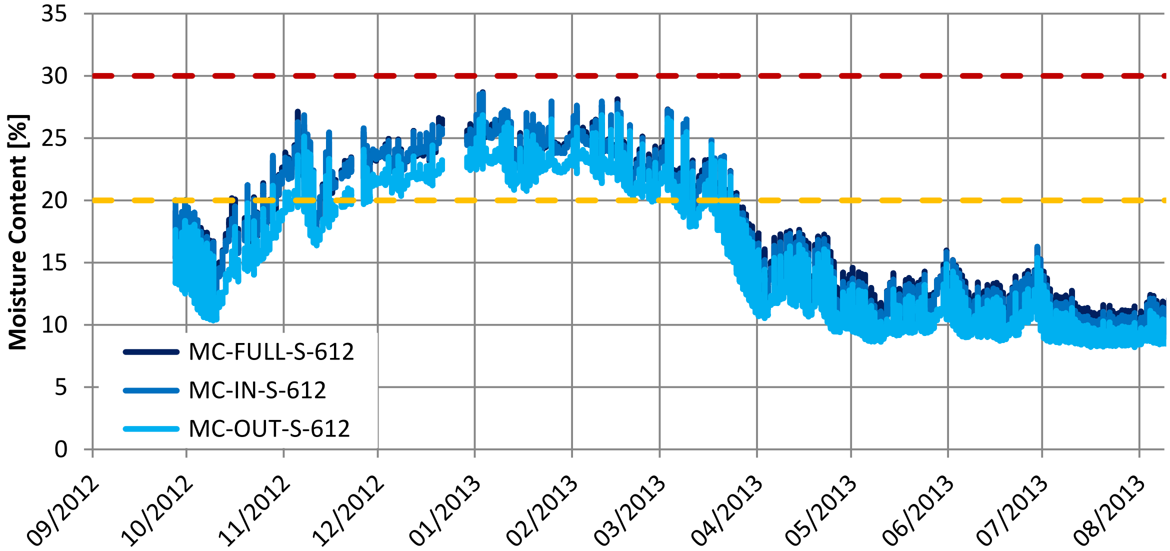

Figure 14 – Moisture Content, South 6:12 Roof, Full, Inner, and Outer Sensors

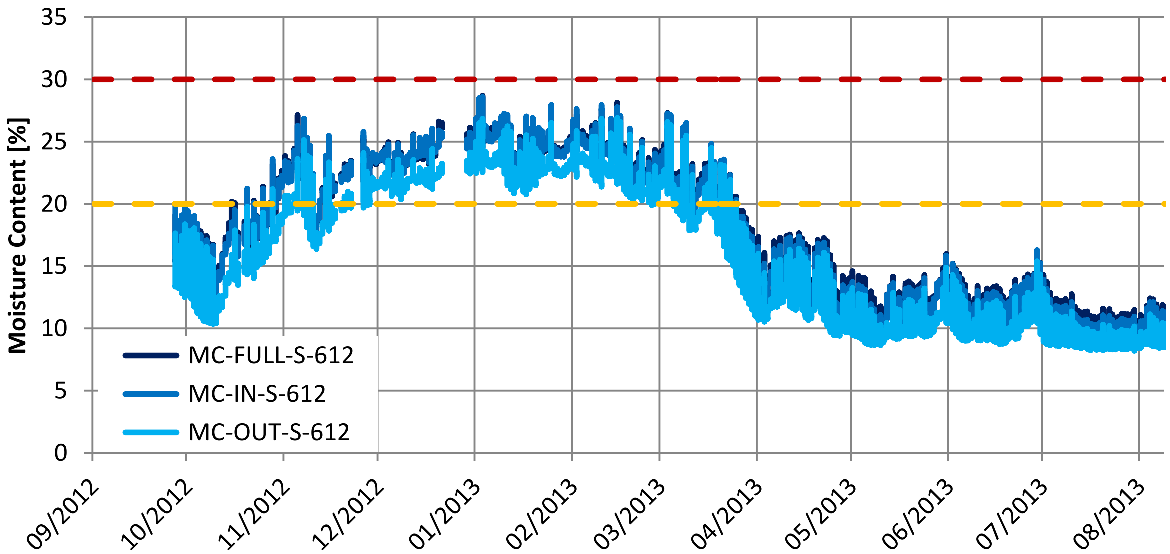

Figure 15 – Moisture Content, North 6:12 Roof, Full, Inner, and Outer Sensors

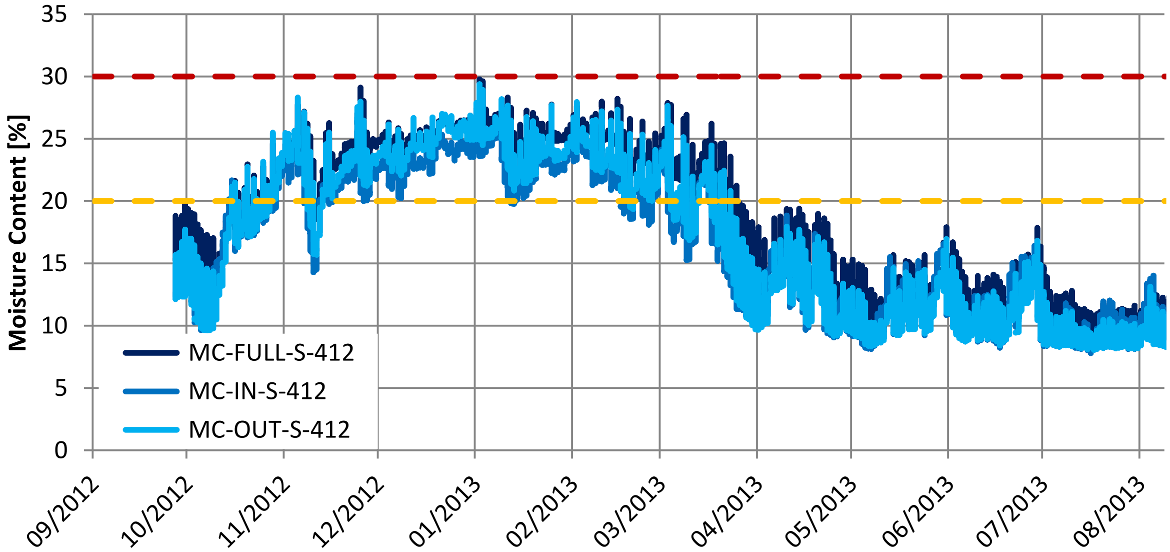

Figure 16 – Moisture Content, South 4:12 Roof, Full, Inner, and Outer Sensors

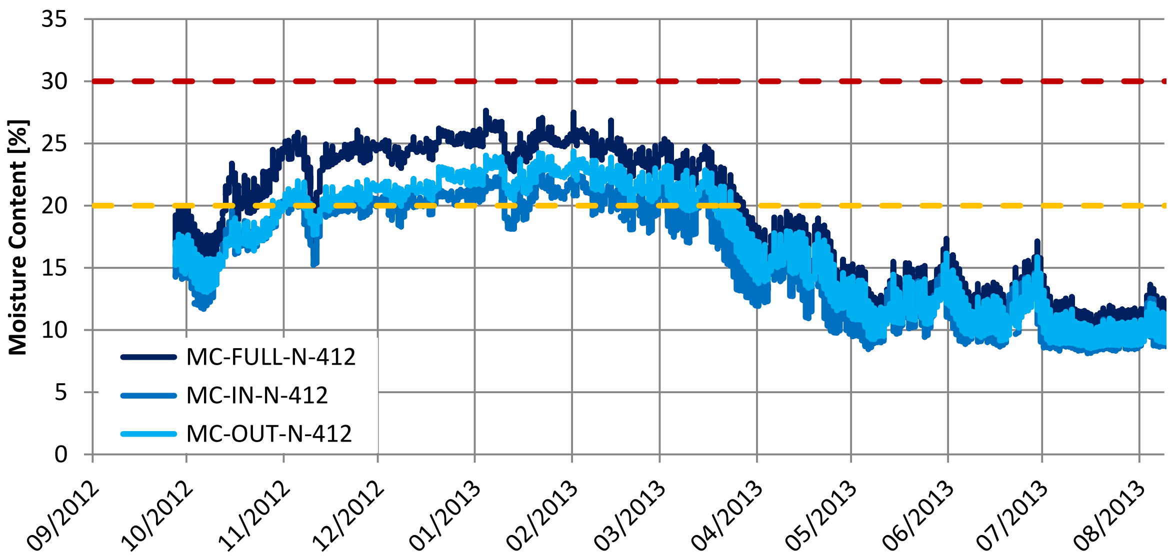

Figure 17 – Moisture Content, North 4:12 Roof, Full, Inner, and Outer Sensors

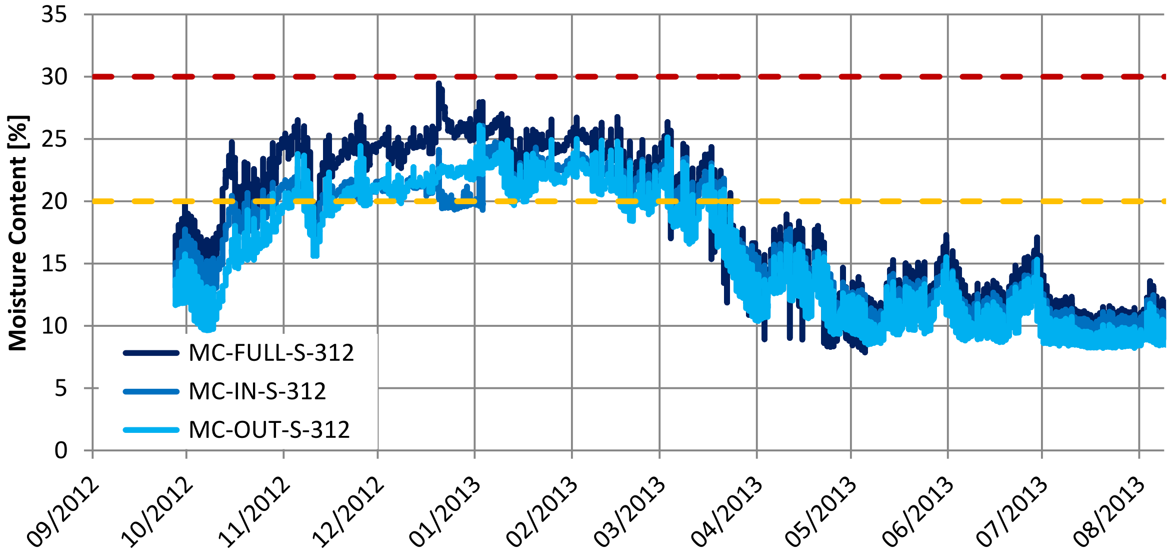

Figure 18 – Moisture Content, South 3:12 Roof, Full, Inner, and Outer Sensors

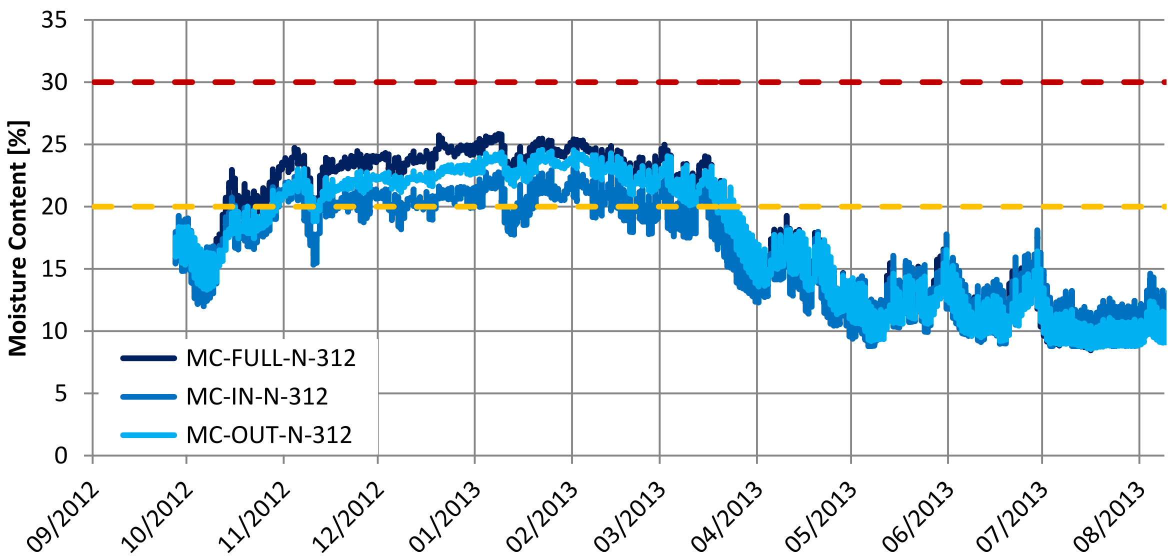

Figure 19 – Moisture Content, North 3:12 Roof, Full, Inner, and Outer Sensors

Temperature

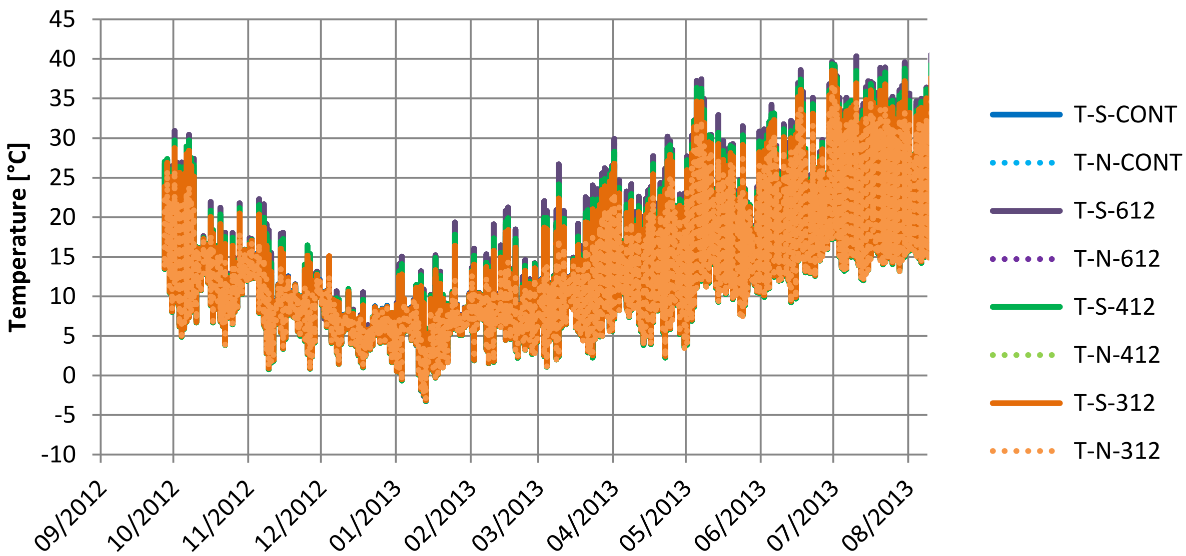

Figure 20 – Embedded Sheathing Temperatures for CONT, 6:12, 4:12, and 3:12 Roofs, North and South Orientation, Full Monitoring Period

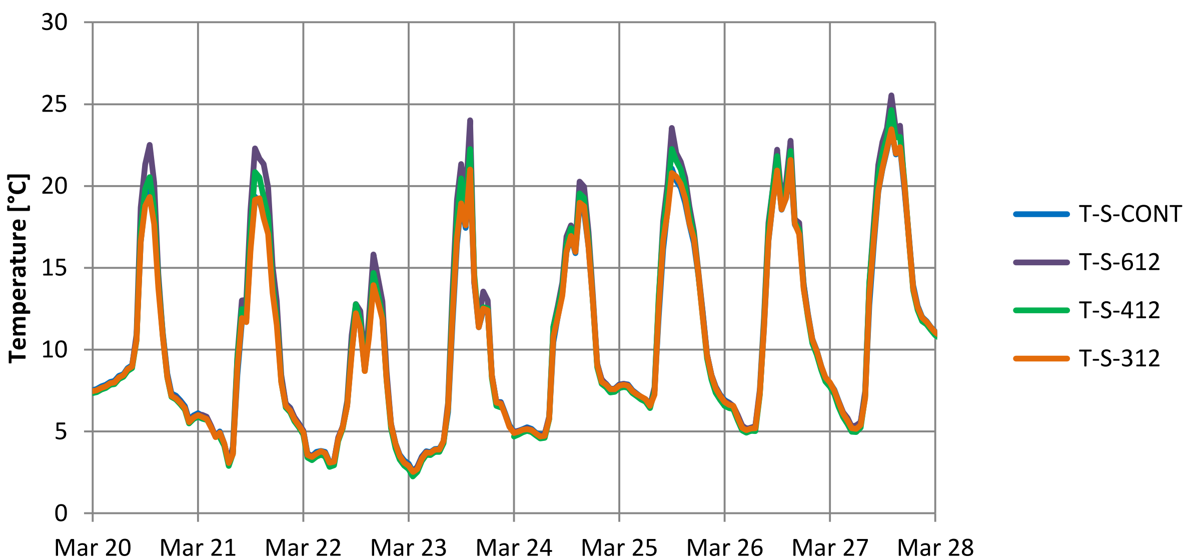

Figure 21 – Embedded Sheathing Temperatures, South Orientation, for CONT, 6:12, 4:12, and 3:12 Roof, from March 20 to March 28, 2013

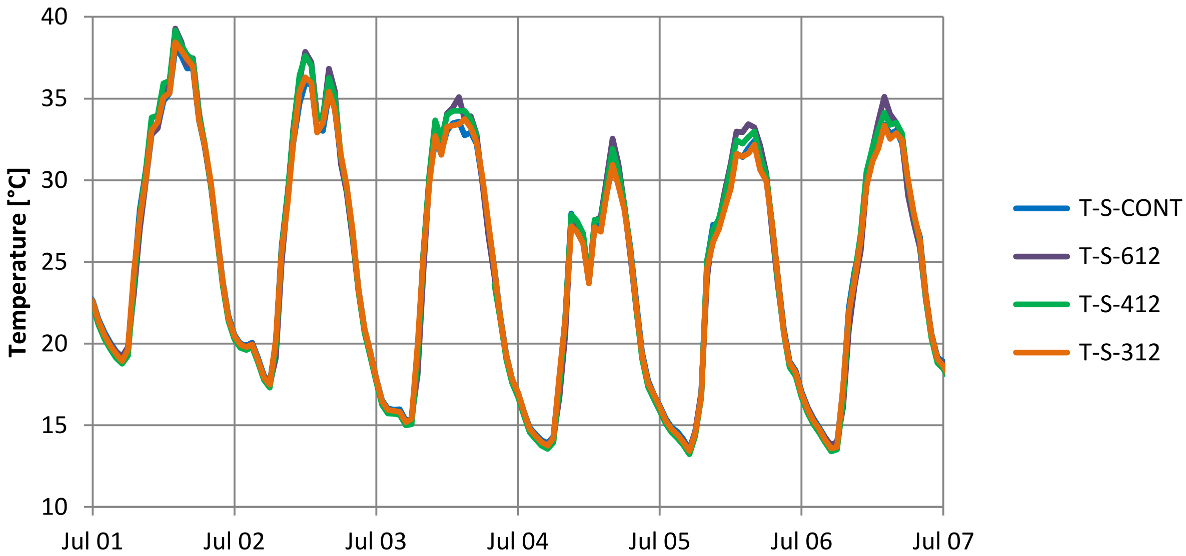

Figure 22 – Embedded Sheathing Temperatures, South Orientation, for CONT, 6:12, 4:12, and 3:12 Roof, from July 1 to July 7, 2013

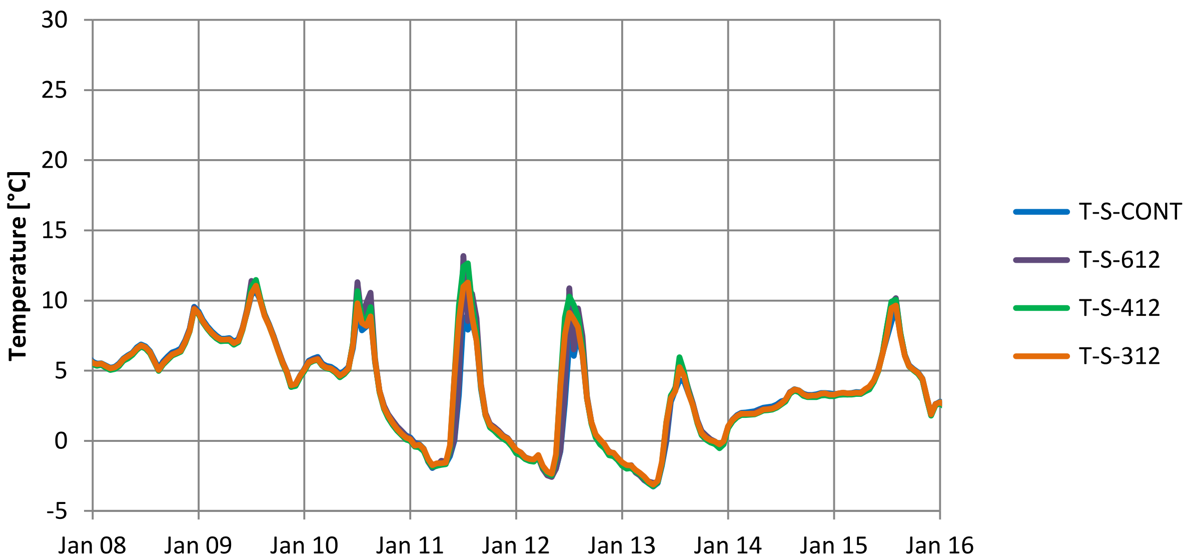

Figure 23 – Embedded Sheathing Temperatures, South Orientation, for CONT, 6:12, 4:12, and 3:12 Roof, from January 8 to January 16, 2013

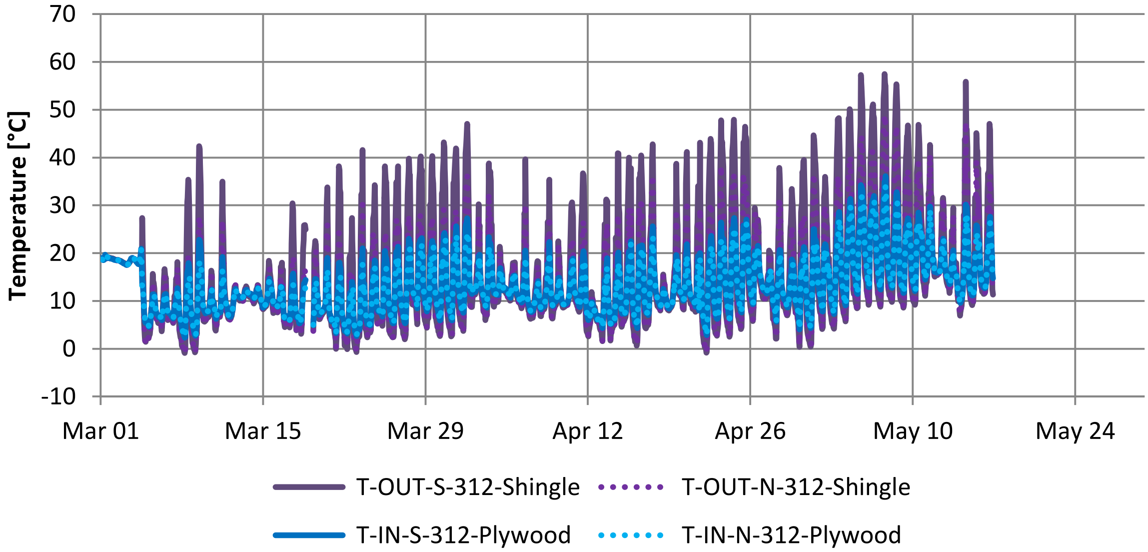

Figure 24 – Shingle and Plywood Temperatures, 3:12 Roof both North and South, from March 1 to May 24, 2013

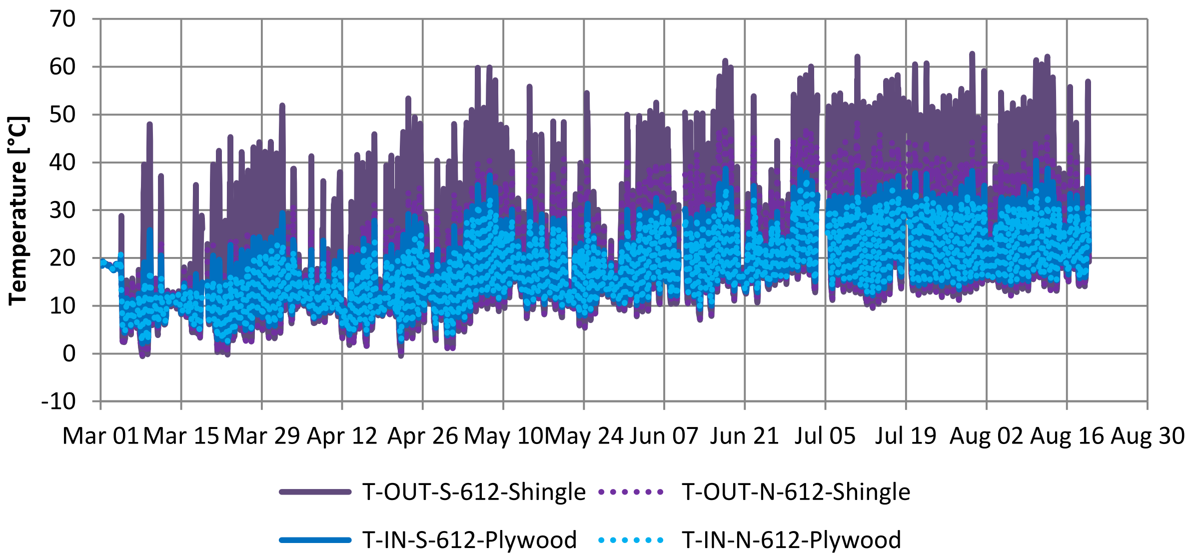

Figure 25 – Shingle and Plywood Temperatures, 6:12 Roof both North and South, from March 1 to August 30, 2013

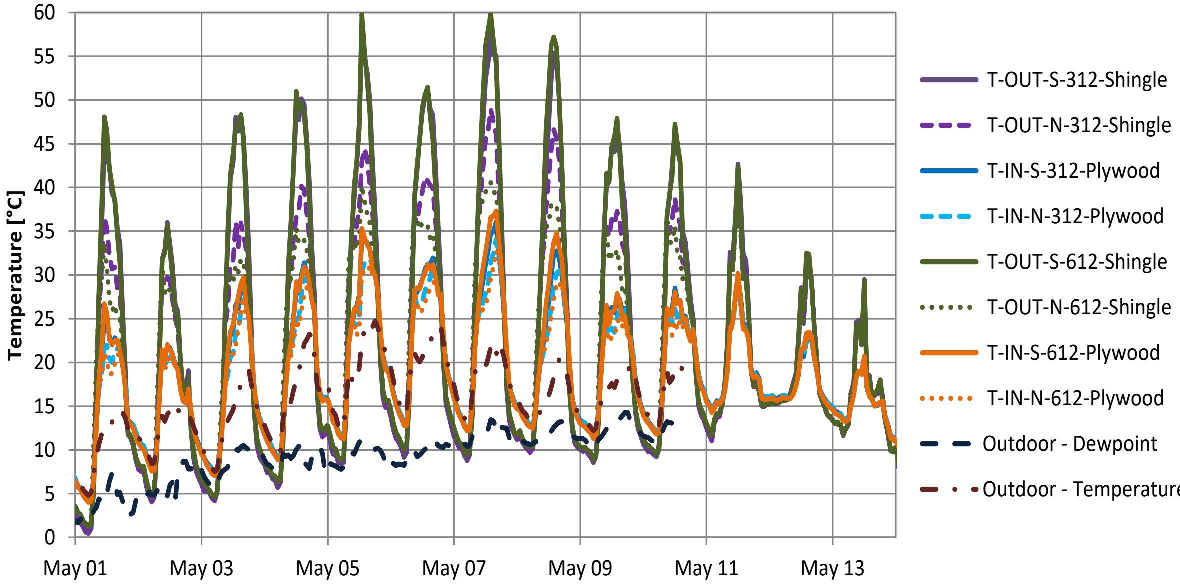

Figure 26 – Shingle and Plywood Temperatures, 3:12 and 6:12 Roofs, both North and South, including Outdoor Dew Point and Sensible Temperatures, from May 1 to May 14, 2013

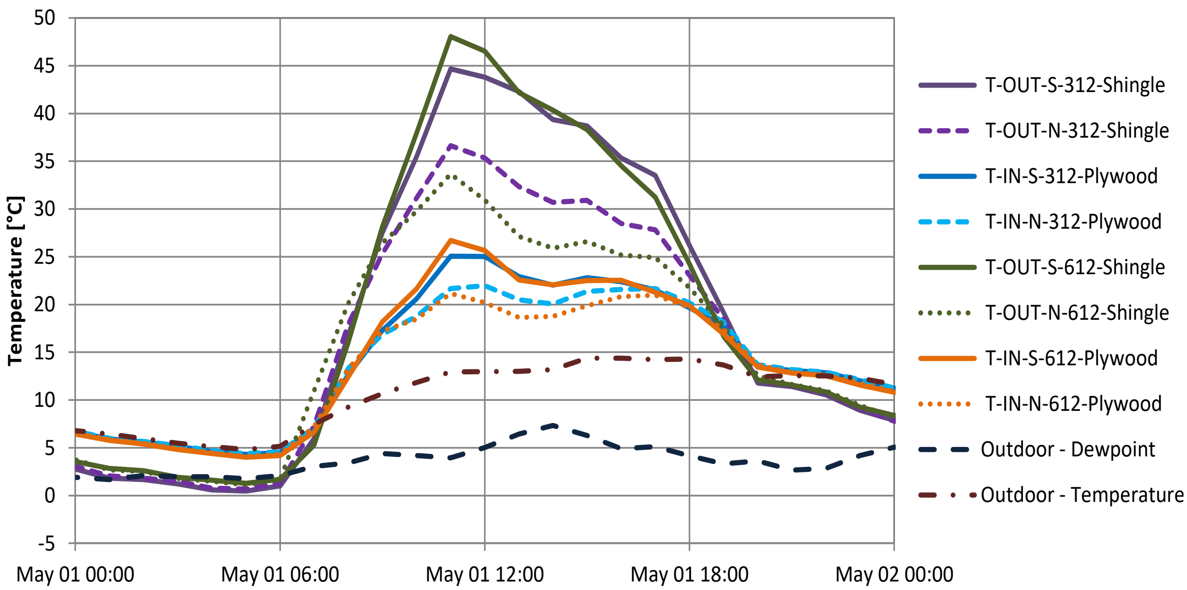

Figure 27 – Shingle and Plywood Temperatures, 3:12 and 6:12 Roofs, both North and South, including Outdoor Dew Point and Sensible Temperatures, May 1, 2013

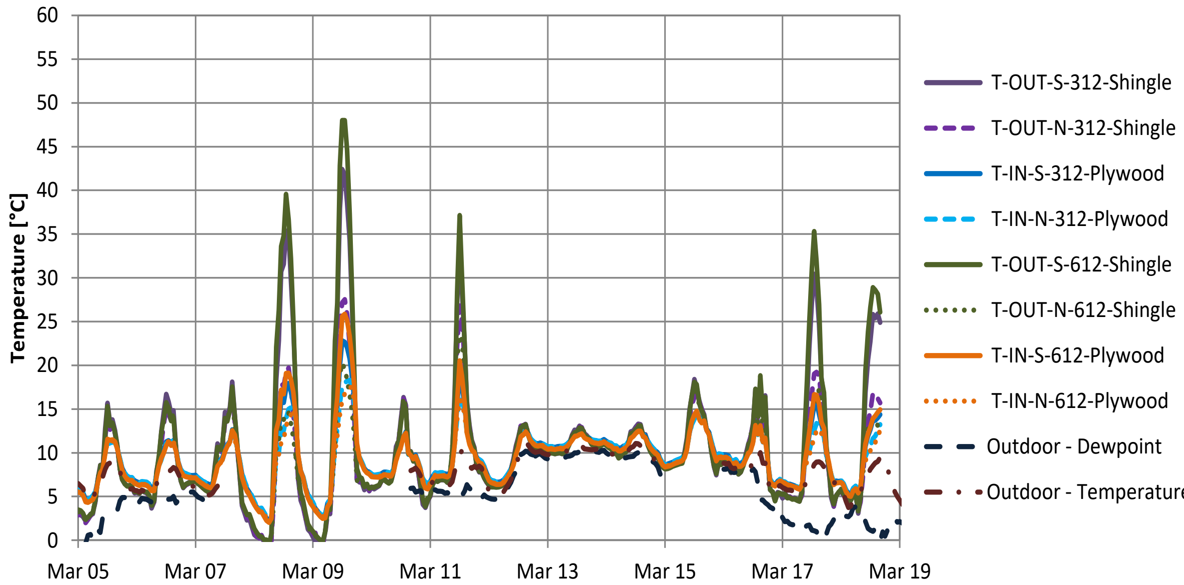

Figure 28 – Shingle and Plywood Temperatures, 3:12 and 6:12 Roofs, both North and South, including Outdoor Dew Point and Sensible Temperatures, March 5 to March 19, 2013

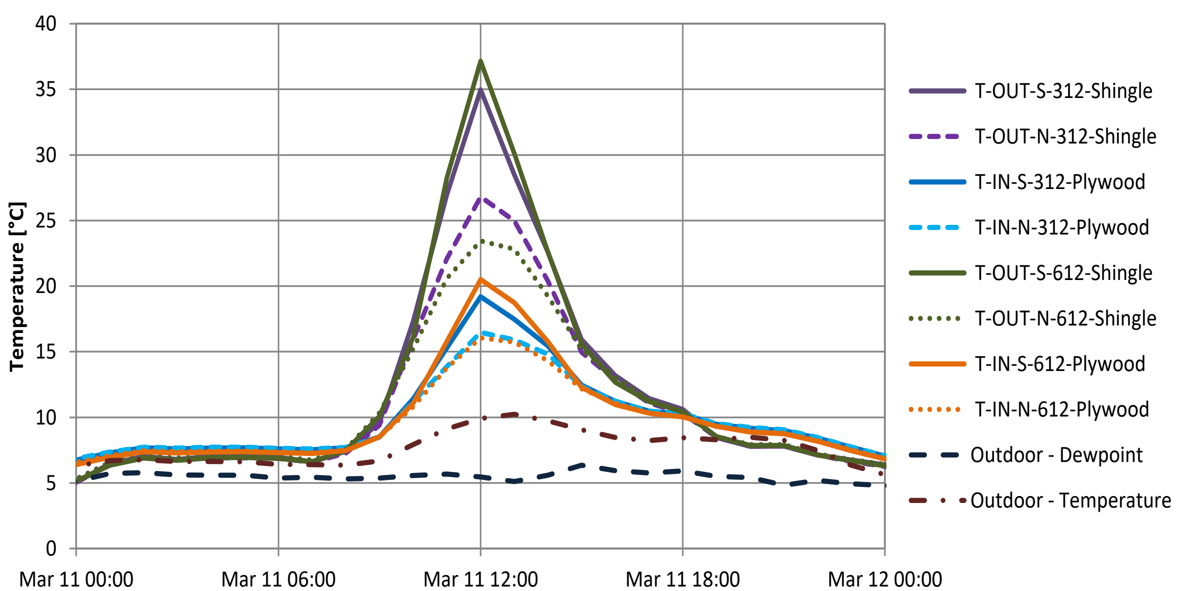

Figure 29 Shingle and Plywood Temperatures, 3:12 and 6:12 Roofs, both North and South, including Outdoor Dew Point and Sensible Temperatures, March 11, 2013

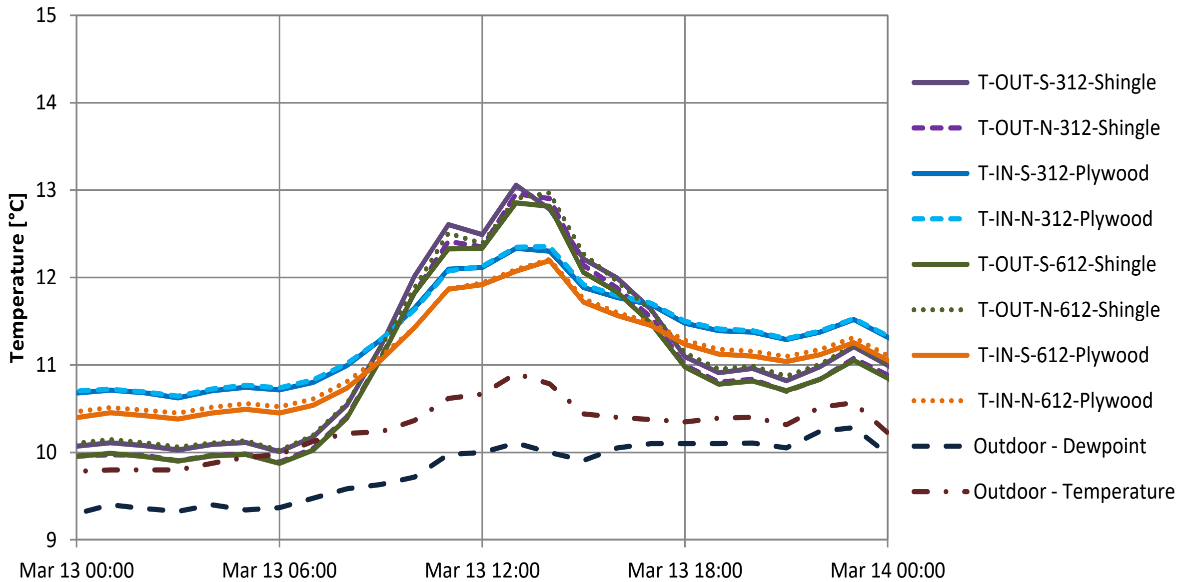

Figure 30 – Shingle and Plywood Temperatures, 3:12 and 6:12 Roofs, both North and South, including Outdoor Dew Point and Sensible Temperatures, March 13, 2013

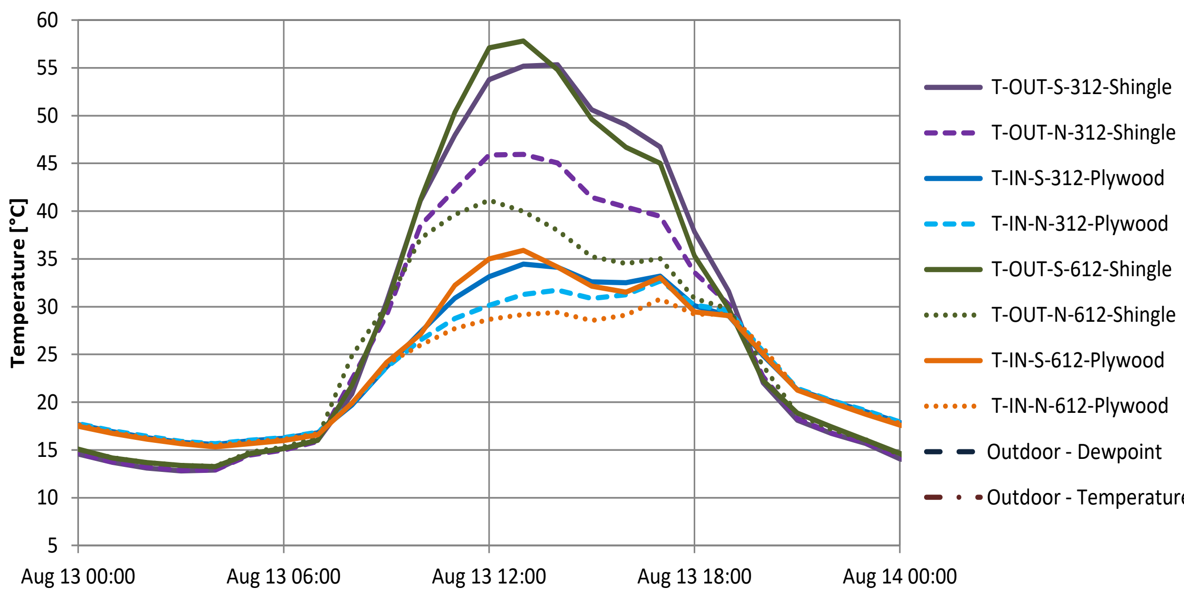

Figure 31 – Shingle and Plywood Temperatures, 3:12 and 6:12 Roofs, both North and South, including Outdoor Dew Point and Sensible Temperatures, August 13, 2013

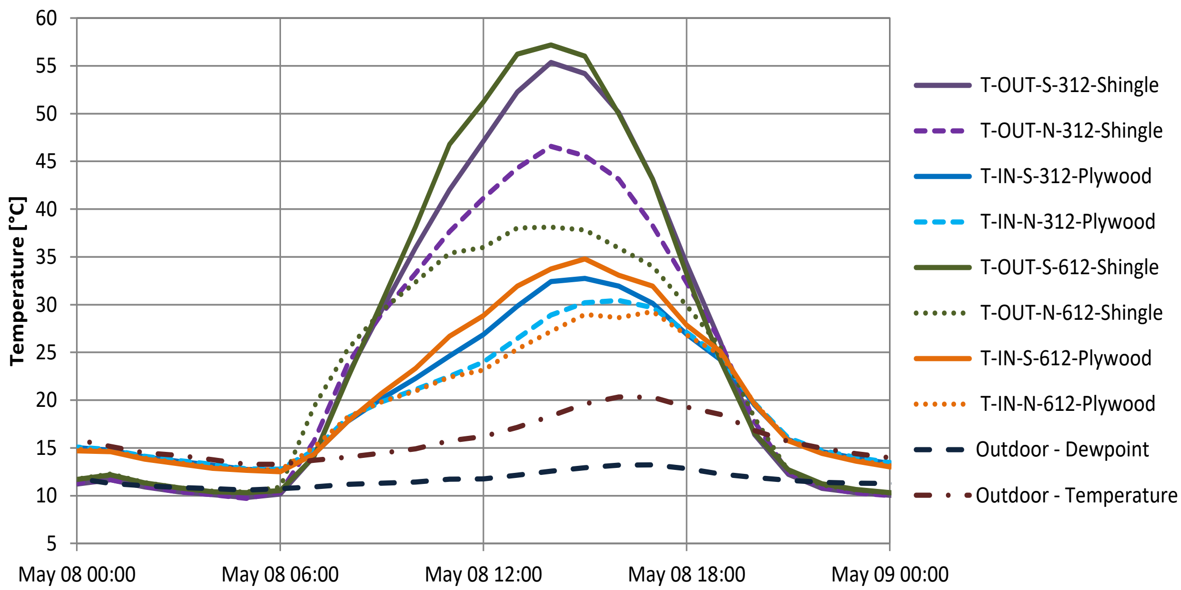

Figure 32 – Shingle and Plywood Temperatures, 3:12 and 6:12 Roofs, both North and South, including Outdoor Dew Point and Sensible Temperatures, May 8, 2013

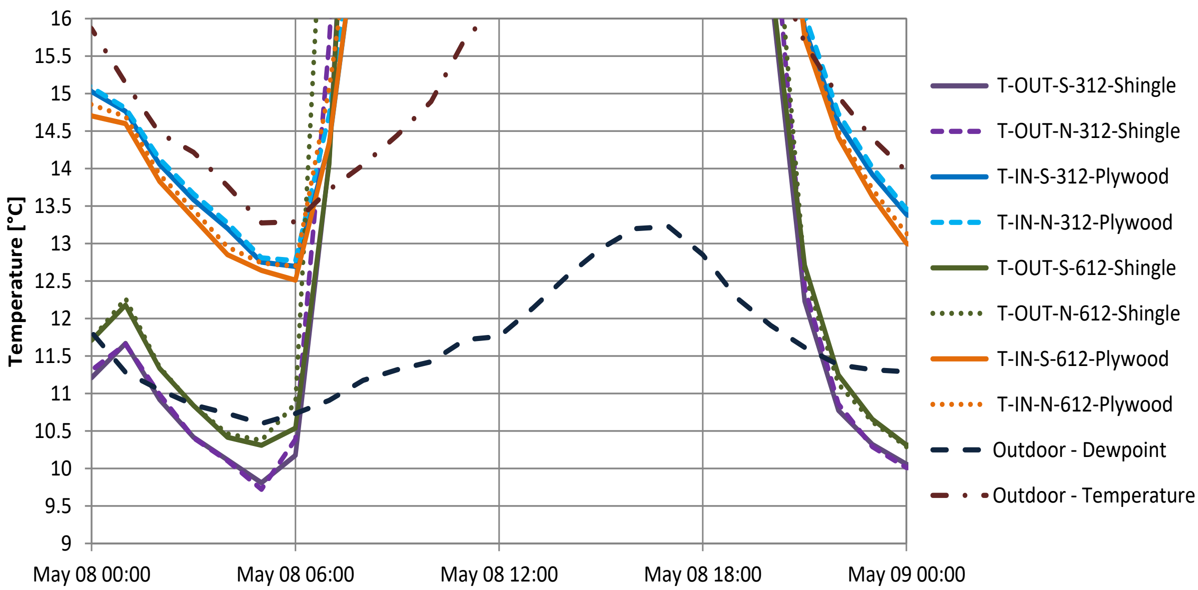

Figure 33 – Shingle and Plywood Temperatures, 3:12 and 6:12 Roofs, both North and South, including Outdoor Dew Point and Sensible Temperatures, May 8, 2013, Showing Condensation

Moisture Content and Temperature– Periodic

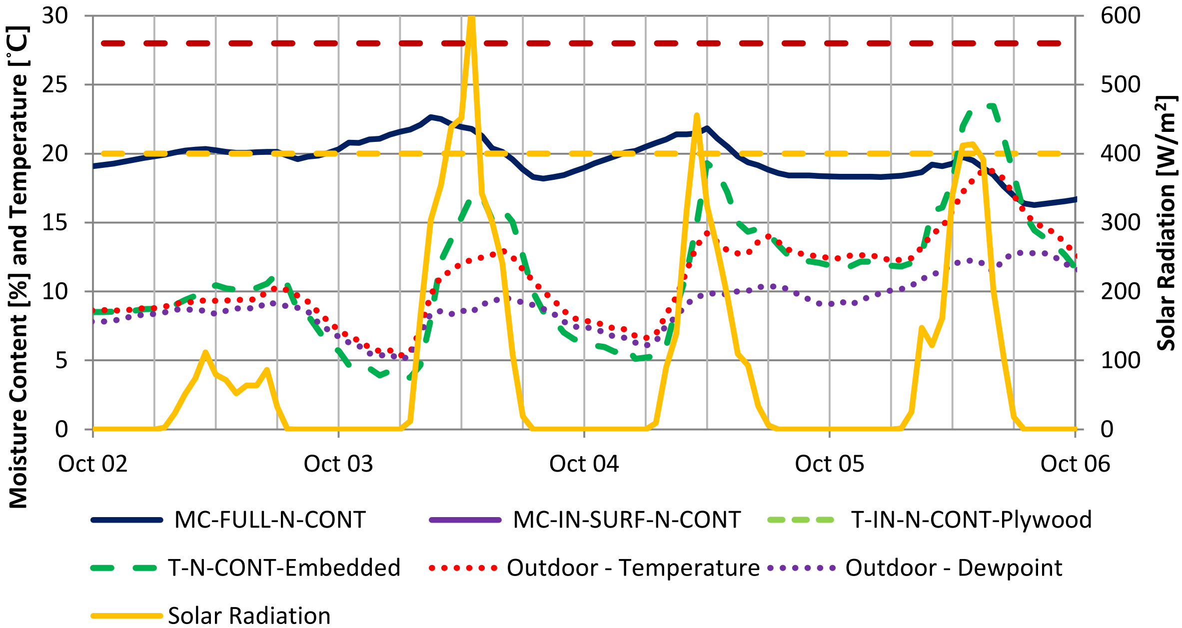

Figure 34 – Moisture Content and Sheathing Temperatures, North CONT Roof, including Solar Radiation, Outdoor Dew Point and Sensible Temperatures, October 2 to October 6, 2013.

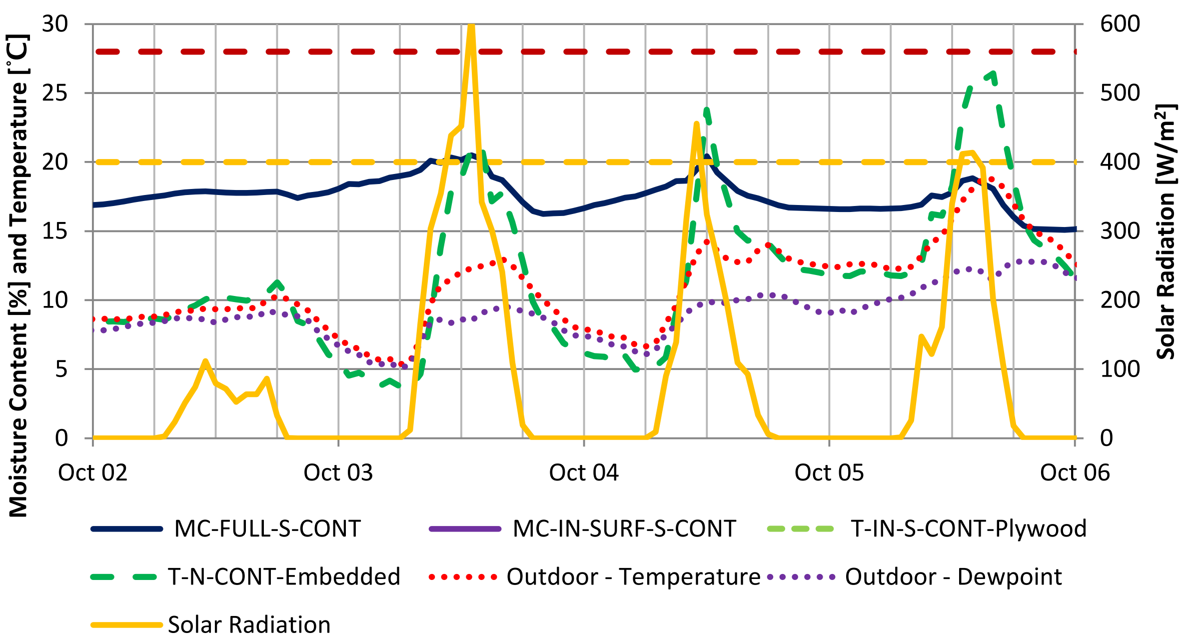

Figure 35 – Moisture Content and Sheathing Temperatures, South CONT Roof, including Solar Radiation, Outdoor Dew Point and Sensible Temperatures, October 2 to October 6, 2013.

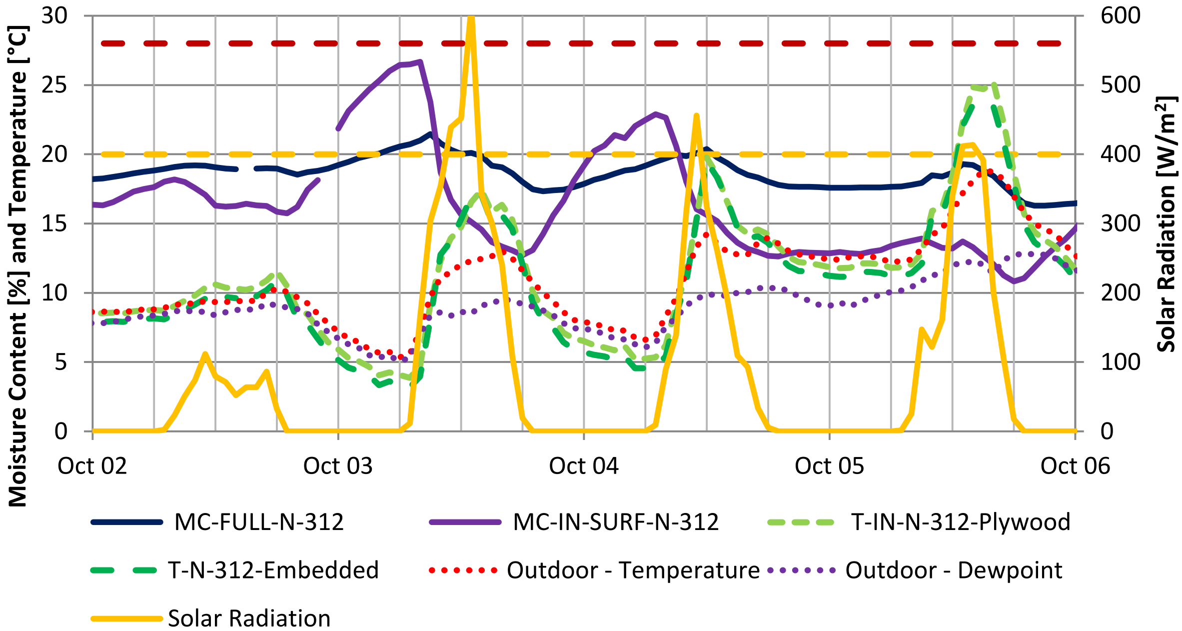

Figure 36 – Moisture Content and Sheathing Temperatures, South 3:12 Roof, including Solar Radiation, Outdoor Dew Point and Sensible Temperatures, October 2 to October 6, 2013.

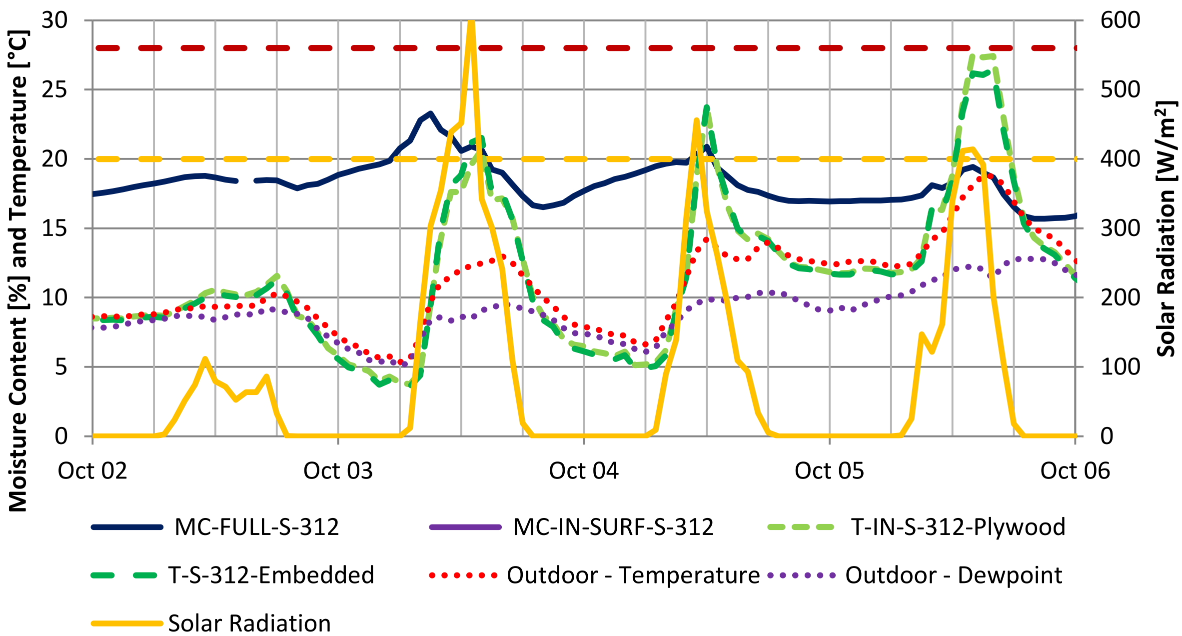

Figure 37 – Moisture Content and Sheathing Temperatures, North 3:12 Roof, including Solar Radiation, Outdoor Dew Point and Sensible Temperatures, October 2 to October 6, 2013.

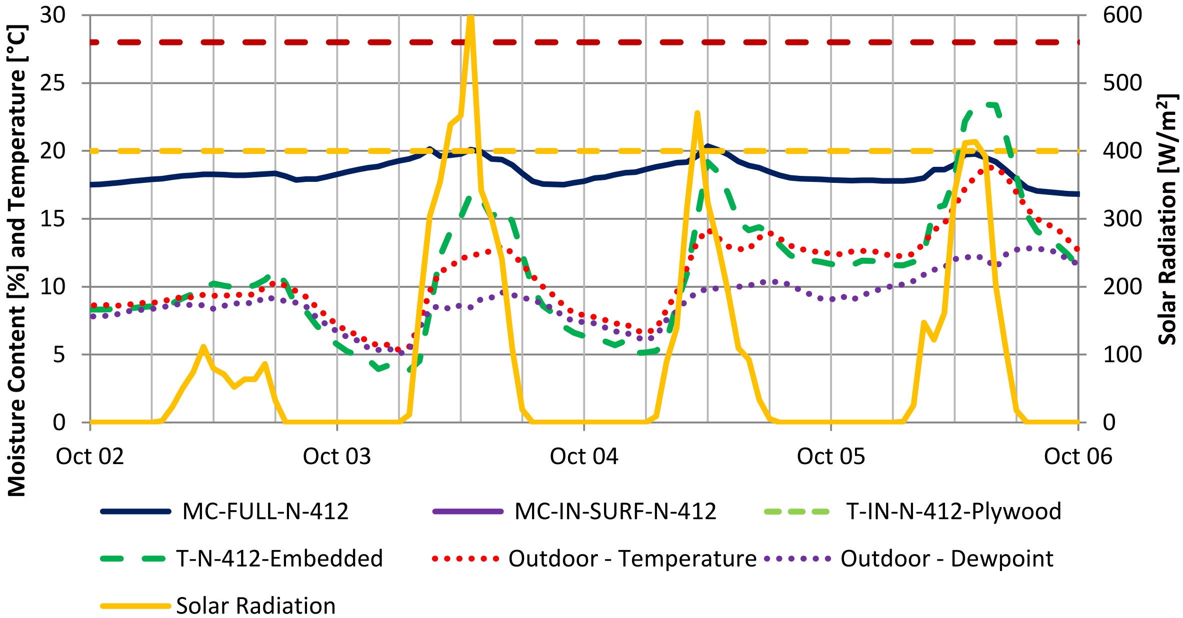

Figure 38 – Moisture Content and Sheathing Temperatures, South 4:12 Roof, including Solar Radiation, Outdoor Dew Point and Sensible Temperatures, October 2 to October 6, 2013.

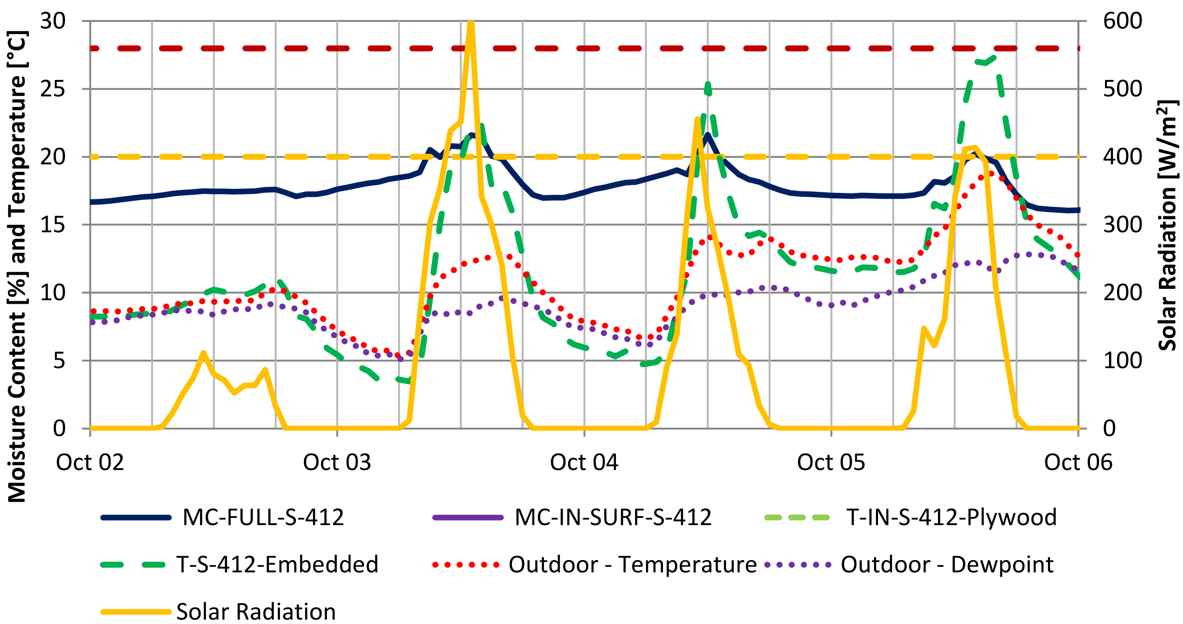

Figure 39 – Moisture Content and Sheathing Temperatures, North 4:12 Roof, including Solar Radiation, Outdoor Dew Point and Sensible Temperatures, October 2 to October 6, 2013.

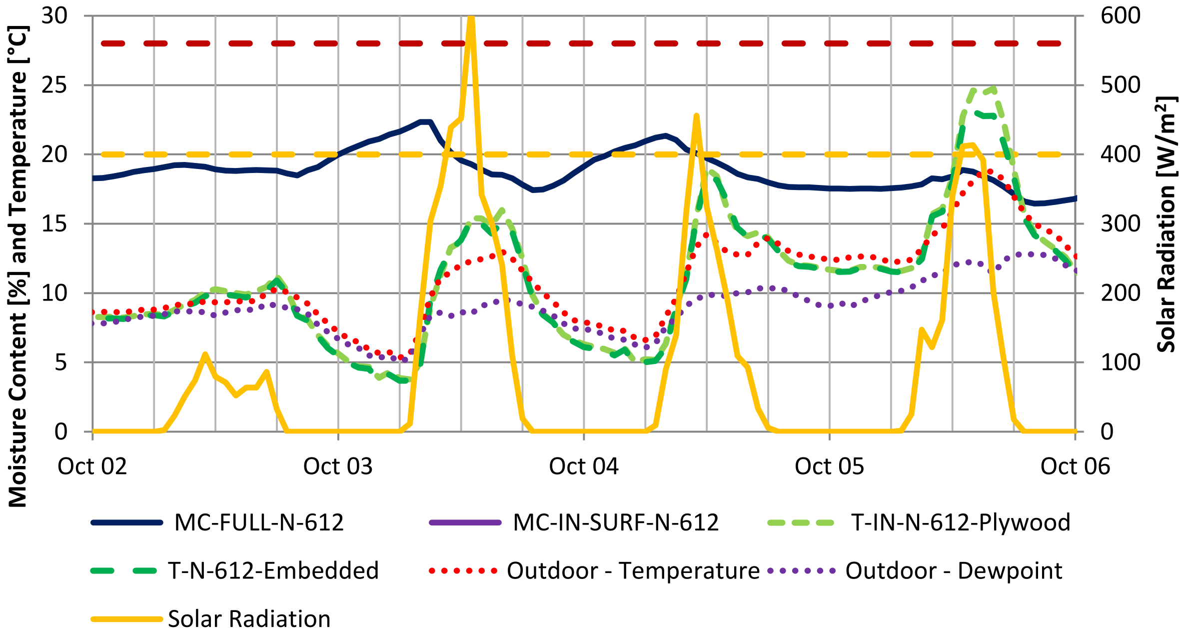

Figure 40 – Moisture Content and Sheathing Temperatures, South 6:12 Roof, including Solar Radiation, Outdoor Dew Point and Sensible Temperatures, October 2 to October 6, 2013.

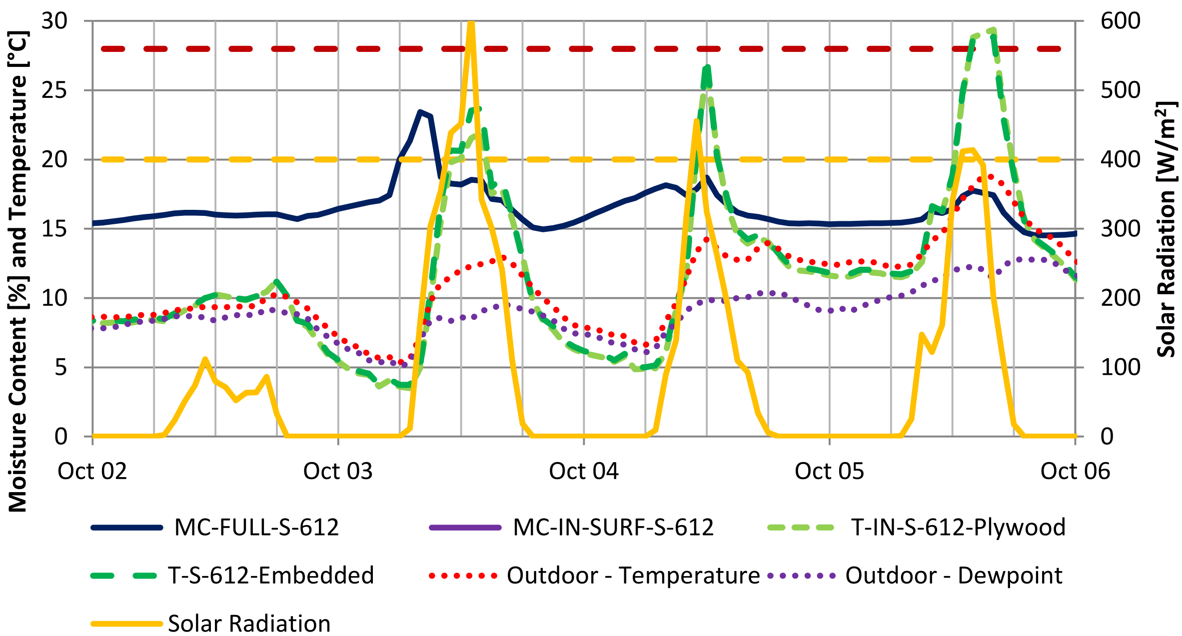

Figure 41 Moisture Content and Sheathing Temperatures, North 6:12 Roof, including Solar Radiation, Outdoor Dew Point and Sensible Temperatures, October 2 to October 6, 2013.

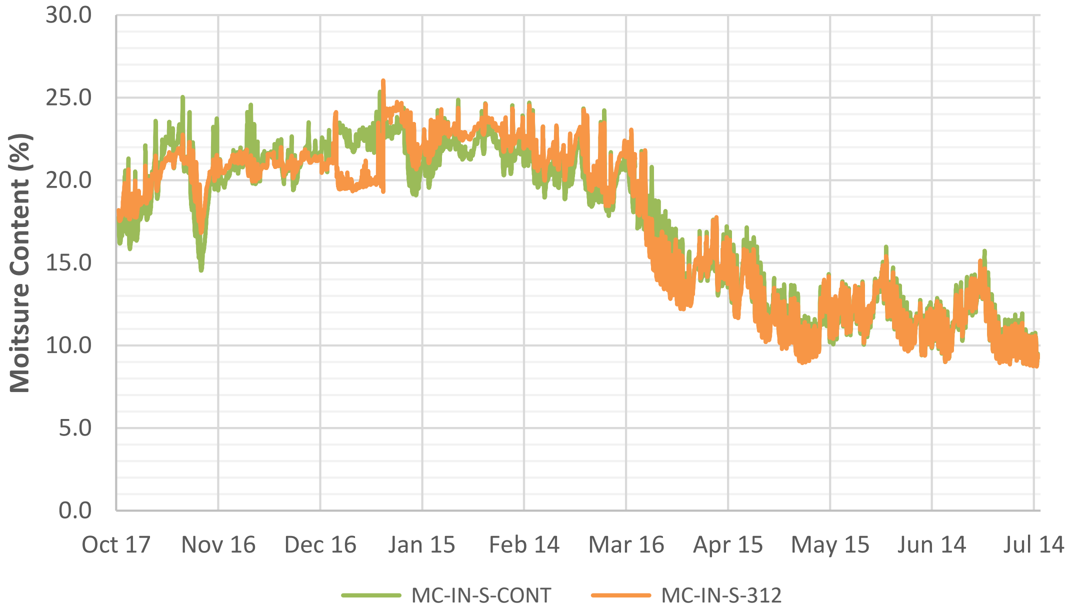

Figure 42 – Moisture Content, Inner 1/8" Depth, CONT Roof, South Orientation

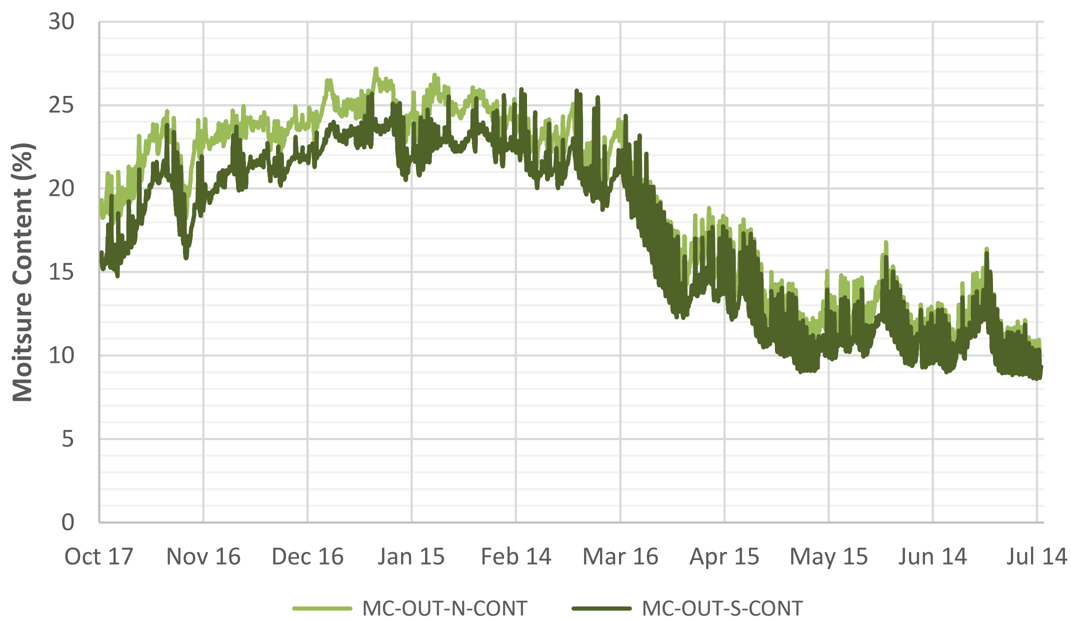

Figure 43 – Moisture Content, Outer 1/8" Depth, CONT Roof, South Orientation

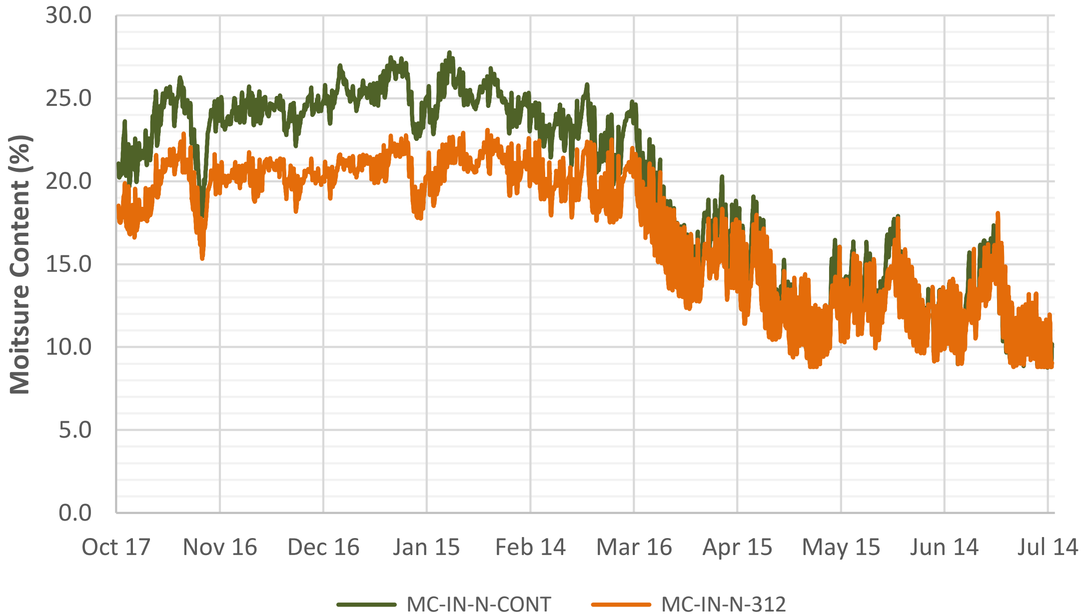

Figure 44 – Moisture Content, Inner 1/8" Depth, CONT Roof, North Orientation

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