HYGROTHERMAL PERFORMANCE ANALYSIS OF DRYOUT RESPONSE ON IN-SITU CROSS-LAMINATED TIMBER AND THE EFFECT ON OCCUPANCY CONDITIONS

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3B Architectural Engineering

January 2024

January 03, 2024

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Dear Dr. Al-Hammoud:

This report, entitled "Hygrothermal Performance Analysis of Dryout Response on In-Situ Cross-Laminated Timber and the Effect on Occupancy Conditions" was prepared as my 3B work term report. This technical report was prepared in affiliation with Toronto Metropolitan University under the supervision of "*Dr. Russell Richman, Professor, PhD, P.Eng, MASc, BASc*". The intent of this investigation and subsequent report was to explore how variations in building envelope strategies enclosing cross-laminated timber (CLT) affects the dryout response of the material.

The investigation focuses on collecting information from a series of assemblies installed on a test hut, to provide in-situ measurements of hygrothermal performance. The principal areas of interest include a phased linear analysis of the dryout phase of various assemblies and a subsequent analysis of the potential mould-risk that may occur from high moisture absorption or slow dryout based on the associated control layer properties or construction practices.

The investigation has successfully provided insightful information that can be used within the mass timber industry, by establishing tangible conclusions that were extrapolated from the readings of moisture content, temperature, and relative humidity within various points of the wooden members. These results provided valuable information to make informed decisions within the design of building enclosures protecting timber and other engineered wood products.

This report was written entirely by me and has not received any previous academic credit at this or any other academic institution. I would like to thank *Dorothy Johns, OAA, CPHC, PhD Candidate, March, BArchSci*, and *Dr. Russell Richman, Professor, PhD, P.Eng, MASc, BASc*, of Toronto Metropolitan University for assisting me during the investigation and review of this report. I additionally would like to recognize the extensive effort of Dorothy Johns within the initial development of the experiment and data acquisition throughout the entire process. I have received no other help with this report.

Sincerely,

Cameron Lawrence

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Summary

This investigation, “Hygrothermal Performance Analysis of Dryout Response on In-Situ Cross-Laminated Timber and the Effect on Occupancy Conditions” studies the effect of a variety of enclosure designs and construction practices on the rate of dryout in cross-laminated timber (CLT) decks. Through this investigation, a quantitative method to assess risk to the health of occupants with respect to mould growth based on increased moisture content levels was developed. The linearization of distinct ranges of moisture content in enclosed panels was analysed to compare the efficacy of enclosure design strategies on limiting peak moisture content while improving dryout rates. Additionally, the analysis involved a linear approximation of average dryout response to assess the quantity of time the enclosed mass timber was at risk of mould growth, subsequently forming recommendations for design strategies to mitigate mould within mass timber in building enclosures.

Table of Contents

List of Figures

List of Tables

List of Appendices

1.0 Introduction

With the increasing efforts to reduce carbon emissions in the architecture, engineering, and construction (AEC) industries recent years, there have been intensive efforts to increase the quantity of mass timber construction as an alternative when steel and concrete design could be considered as obsolete. With this surge of mass timber construction, codes and practices have been and continue to be updated to allow for larger and more impressive structures to be made from mass timber and engineered timber products, where in recent years it would have been the assumption of a structural engineer that a 20-storey building must be made from well established material such as steel reinforced concrete.

Initiatives such as British Columbia's Wood First Act (Government of British Columbia, 2023), were developed to promote the local timber sector while promoting construction that is increasingly beneficial for the environment. This has encouraged the AEC industry professionals to further explore and push the extent we can use wood for within construction practices, proving as a method for rapid innovation in the space.

Recent construction has demonstrated the impressive usage and modern understanding of innovative structural engineering, as all-timber construction reached heights of 85.4m, as the Mjøstårnet, an 18-storey mixed-use building in Brumunddal, Norway was completed in 2019, or as timber-concrete hybrid structures reached heights of 86.6m, when in 2022 the construction of Ascent, a 25-storey residential building in Milwaukee, USA was completed (CTBUH, 2022).

1.1. Mass Timber Construction

All construction products have variations in performance based on their inherit material properties that provide advantages and disadvantages, making different materials better in specific applications than their alternatives based on the context. Concrete is extremely strong in compression and has high fire-resistance, but is poor in tension, whereas steel is extremely strong in tension but has poor performance under high temperatures. Wood has been a popular building material historically due to its abundance and ease of construction in light wood-framing due to its redundancy from a structural engineering perspective. It is still known to be easily installed and durable, however, as construction has become increasingly innovative and the demand for unique and impressive architecture has risen, concrete and steel have become the material of choice for large construction and even making its way into residential through products such as insulated concrete forms (ICF).

The carbon and energy intensive processes to develop steel and concrete is the principal drawback from predominately using these materials in more applications. Although there are extensive efforts towards reducing the carbon emissions in products such as Portland cement-based concrete, wood is natural and known as a “carbon sink”. A carbon sink describes a material that captures atmospheric carbon dioxide and stores it within its fibers through a process called carbon sequestration. With respect to the sequestering properties available in timber construction, steel and concrete are generally considered much worse for the environment than wood. This explains the increasing focus and consideration on mass-timber construction as an alternative wherever it is plausible to an equivalent concrete or steel structure.

Wood is a hygroscopic material, as it absorbs and holds moisture. However, moisture content can quite drastically impact characteristics of timber and form growth characteristics. These changes and growth characteristics can cause boards to deform in various ways and may impact the expected performance of the material. As wood seasons, it experiences differences in moisture content through the absorption of water and dryout response. As water is absorbed, the water molecules are introduced in the plenum between the chains of cellulose in the cell wall, causing expansion. Similarly, as the wood dries and these water molecules are removed, the cellulose chains tighten and cause shrinkage. However, wood is regarded as an orthotropic material, such that has distinct properties in its perpendicular directions in planar orientation (longitudinal, radial, tangential) as demonstrated in **Figure 1**.

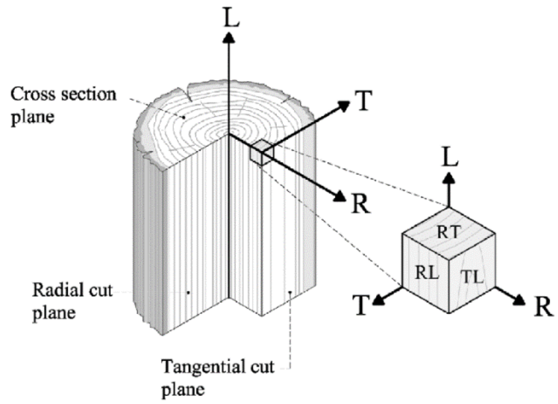

Figure 1: Planar Orientation of Wood (Lara-Bocanegra, 2022)

1.2. Hygroscopic Properties of Wood

Hygrothermal simulation modelling is a form of analysis often conducted with computer programs that can model the short-term and long-term effects of moisture and temperature conditions on a structure. The analysis has demonstrated to be a powerful tool in predicting issues that may occur within assemblies or structural components of a building. Often within the building science industry, these models are used to provide information on the longevity of structures and are useful in assisting in identifying faulty construction practices that are intended to design against the migration of moisture and vapour diffusion.

Wood as a building material causes unique complexities relative to a material such as steel due to its hygroscopic properties, as previously introduced. Similar to concrete, wood is porous and can fill with liquid water or water vapour. However, concrete is not negatively impacted by water in the same way as timber products. Whereas concrete is susceptible to free-thaw cycles that can introduces cracking of the material, wood naturally is susceptible to rotting if exposed to moisture for extended periods of time, explaining the recent demand for the ability of dryout within the assembly of building enclosures. This has become an increasingly important issue due to failures of structural and envelope systems and has prompted recommendations of building scientist to shift on materials such as vapour retarders, such that the modern suggestion can be explained to use as permeable of a material as possible while maintain sufficient performance. This is demonstrated by the following recommendation for building enclosures (Lstiburek, 2011):

> *"Avoidance of using vapor barriers where vapor retarders will provide satisfactory performance. Avoidance of using vapor retarders where vapor permeable materials will provide satisfactory performance. Thereby encouraging drying mechanisms over wetting prevention mechanisms."*

Generally, the principal recommendations for the design of building enclosure based on the modern understanding of moisture migration is to prevent water from penetrating into an assembly as much as possible while allowing the water to escape by promoting dryout. In terms of preventing the negative implications of water migration into a building, if an enclosure design can encapsulate these two concepts, it will be successful for water control.

1.3. Post Occupancy Health

Rot is not the only issue caused my excessively high moisture content for prolonged periods of time in timber construction products. If the conditions are present for rot to occur, wood is also susceptible to mould growth. More specifically, wood-decay fungi may begin occurring when wood has a moisture content in excess of 20% (Hellevang, 2011), whereas mold may grow if the material experiences moisture contents above 15% while relative humidity levels are above 60% (Environmental Protection Agency, 2024). Although mould may not directly affect the performance of wood, it serves as a complication for the health of occupants. Mould is alarmingly common in buildings, where in the United States alone 47% million buildings have unhealthy levels of mould growth based on the population weighed average prevalence of dampness or mold (Lawrence Berkeley National Laboratory, 2024). Mould growth is known to affect individuals different but are commonly correlated with allergies, lung irritation, respiratory infections, or asthma (New York State Department of Health, 2023). Some less common effects can include serious infections or illness. Although relatively uncommon, individuals with severely suppressed immune systems may be seriously affected.

It is extremely important, not only for those with weakened immune systems, but general health of building occupants and the general public that mould be a critical design consideration when using materials whereas mould growth may be prevalent, such as timber construction products. Hygrothermal modelling is a useful tool to assist in ensuring assemblies have sufficient performance in relation to dryout response, by preventing water from entering to a high extent, but also allow water to escape that may have potentially migrated into the assembly.

1.4. Scope + Objective

Within this investigation, the principal objective for the experimentation and subsequent analysis is to identify the risk of mould growth based on internal and environmental conditions. In doing so, the aim is to assess occupancy health risks that occur when using timber construction products in the assembly of a high-performance enclosure. This investigation involved isolating the scope to include the analysis of only a cross-laminated timber (CLT) deck that would include three embedded sensors, measuring temperature, relative humidity, and moisture content in distinct layers within the CLT. To assess the risk posed by increased moisture, eight varying assemblies were installed on zoned areas of an enclosed test hut and periodically loaded with water. The embedded sensors have collected readings since May 2022 and within this investigation, phased linear analyses were conducted to measure the response of three distinct ranges of moisture content and the associated rate of dryout, along with the peak moisture content measured within each assembly. The intent is to measure which assemblies reach a peak moisture content within a mould growth risk area, 15% or higher, and how fast the CLT dries out to a moisture content below 15%, whereas mould is no longer a concern. The intent is to develop understanding of how practices such as venting assemblies or using membranes with different permeabilities react to high levels of moisture, so that recommendations can be developed for building enclosures to protect occupants from mould in timber buildings.

2.0 Engineering Application

This section involves a description of research methodology, including controlled measures, a procedural description of the enclosure installation of the test huts and data acquisition practices.

2.1. Research Methodology

The ongoing research with Toronto Metropolitan University includes three phases as indicated in **Figure 2**. Within this investigation, Phase 2 is the primary area of interest, whereas the focus will be on the enclosure of the test hut, whereas data acquisition of the in-situ conditions can be analyzed. Additionally, the spline performance will be omitted from this analysis as the complexity of the analyses

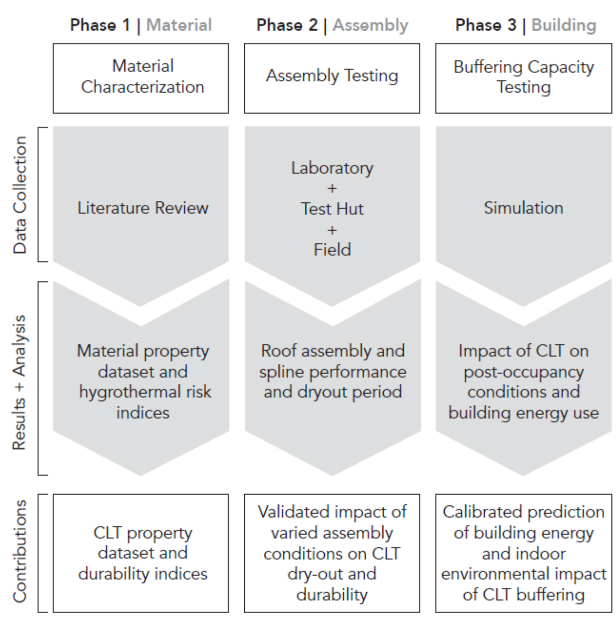

Figure 2: Phases of Research (Johns, 2023)

associated with it deserves more attention and a larger focus.

The analysis will include measuring the dryout response of eight panels installed on the test hut, with various materials and design strategies with the intent to identify which practices can be deemed to have a higher performance. Each panel will be subject to increased moisture content levels through inundation, or flooding, of 25mm ponding water for two months. Following this, the panels will be dried out and installed to the test hut and monitored remotely.

The primary goal is to test and identify if specific assemblies or practices provide the environment to risk mould growth, and how quickly it can dry out of the mould growth zone. This is completed by comparing moisture content readings over time and using the average dryout rate to predict the period of time each assembly takes to dryout from peak moisture content to below 15%, whereas mould is no longer a risk, an example can be seen in **Figure 3**. Additionally, the accuracy of simplified linear predictive models will be compared to the readings through a coefficient of determination (R^2).

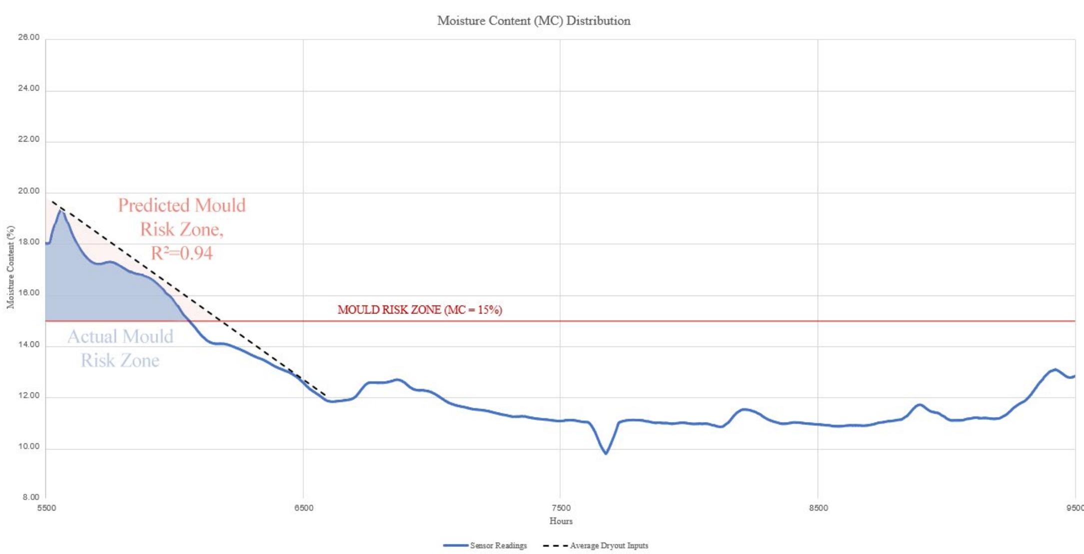

Figure 3: Sample Moisture Content Distribution for Mould Risk

2.1.1. Test Hut Enclosure

The experiment conducted includes the construction of a timber test hut with a cross-laminated timber (CLT) deck, such that the structure can be enclosed, and the in-situ conditions can be analyzed. A photograph of the construction process can be seen in **Figure 4**.

Figure 4: Construction of Test Hut (Johns, 2023)

The structure consists of standard lightwood framing in the walls. The CLT deck is configured of 5-plies with thickness of 35-15-35-15-35mm. To create the appropriate conditions in which the nature of the investigation demands, such that the roof can be appropriately zoned to allow analysis of various enclosure designs, the deck was separated into sixteen 610mm x 610mm panels as can be seen in **Figure 5**, where the highlighted panels are the eight that will be enclosed. The purpose for this is to be able to pre-fabricate the entire set of enclosure panels and flood each assembly prior to installation on the test hut and to separate the panels with an acrylic barrier to prevent water migration or leaks that may affect the data readings.

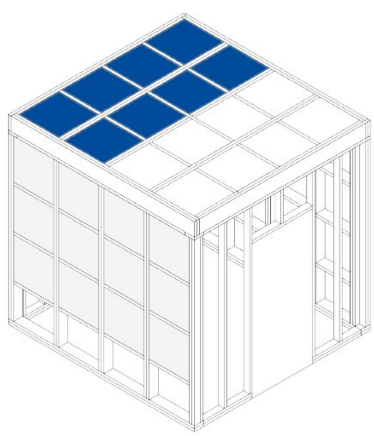

Figure 5: Test Hut Schematic, Modified from (Johns, 2023)

2.1.2. Controls + Variables

The testing of the assemblies aims to measure quantifiable differences in dryout rates between eight (8) enclosure designs and qualitatively describe the variation through fundamental building science principles. The eight distinct enclosure designs were created through installation differences based on the following test variables as shown in **Table 1** .

Table 1: Description of Independent Variables

Variable	Description	Option	Identifier
Coupling	Decoupling refers to the presence of 25mm air cavity, whereas dryout was promoted laterally between panels. Whereas coupling indicates no assistance through an air cavity. ***Note***: *The air cavity is not explicitly ventilated to reduce the addition of additional variables, but is intended to allow increased movement of air flow*	Coupled	**CC**
		Decoupled	**DC**
Vapour Retarder	Vapour retarders with two distinct classes were used to promote (Class III, >10 perms) or restrict (Class I, < 0.1perms) dryout. The class III, or permeable, membrane is the Henry Bakor VP160 (29 perms), and the class I, or impermeable, membrane is the Soprema Sopraseal Stick 1100T (0.037 perms)	Permeable	**PM**
		Impermeable	**IM**
Moisture Protection	Refers to whether or not the vapour retarder was installed prior to inundation, serving as protection from the increased moisture content.	Protected	**PR**
		Unprotected	**UR**

Based on these variables and by factoring in in the concept that the protected and unprotected assemblies will differentiate with respect to the membrane permeability, eight (8) unique assemblies were constructed as shown below in **Figure 6**:

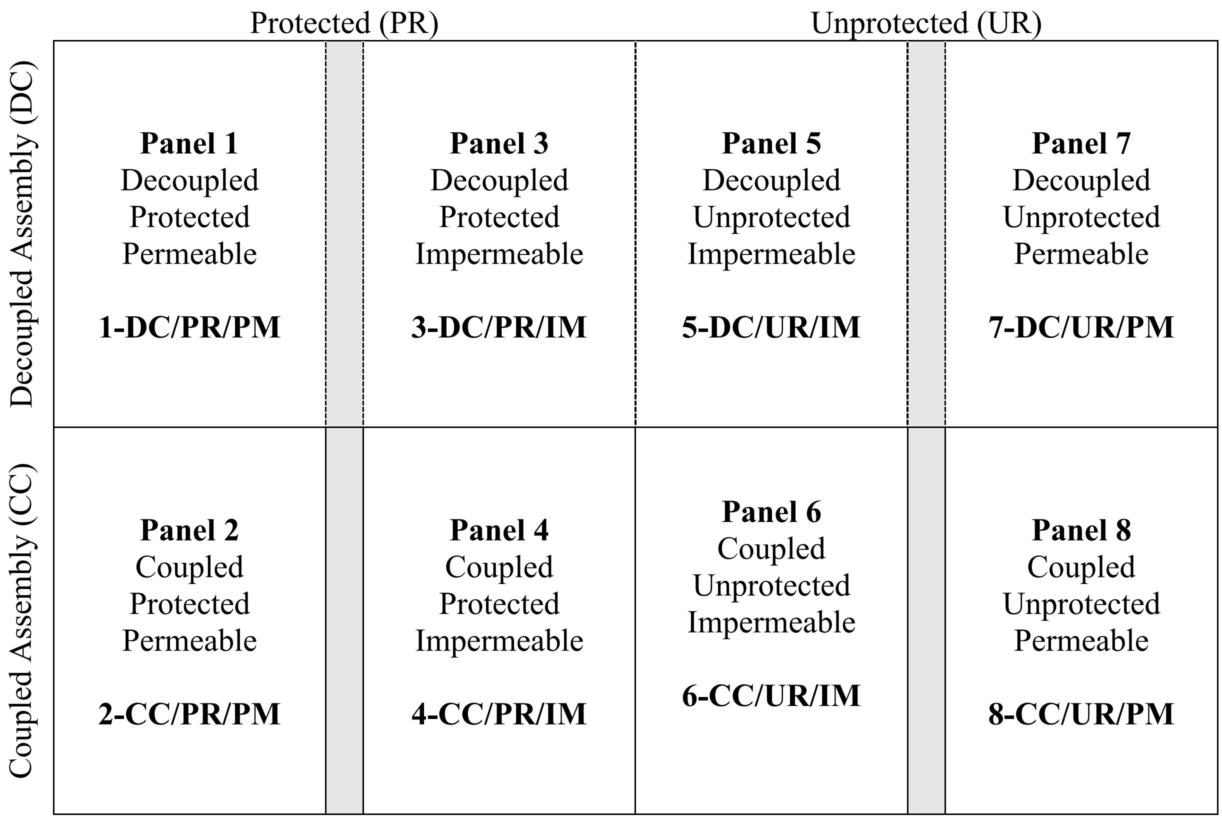

Figure 6: Panel Layout

In order to test the extent to which each of these variables impact the dryout response of the cross-laminated timber (CLT) deck, additional variables that may impact the data acquisition processed needed to be controlled. Firstly, the period of exposure to the exterior environment was equivalent at four months after construction of the prefabricated panels. Secondly, exposure to moisture through the inundation process was consistent, as the panels were flooded for 2-months with 25mm of water. Thirdly, the monitoring period of the enclosed test hut upon installation for the eight panels was consistent at one-year. Fourthly, the panel composition was equal between all panels, including the nominal dimensions, panel manufacturer, and impermeable perimeter edge treatment (elastomeric asphalt emulsion liquid-applied waterproofing) were consistent. Fifthly, the process to install data monitoring equipment were identical between panels, including the quantity and depth of the probes to ensure data acquisition provide an equivalent basis for comparison. Finally, the environmental and interior conditions experienced were equivalent for all panels, ensuring measurements such as relative humidity were not varied in localized areas, impacting one sensor more than another. Additionally, the relative humidity was kept within the range of 55-85% throughout the monitoring period, to maintain relatively high humidity conditions whereas mould may be an issue.

2.1.3. Data Acquisition

The process of data collection utilizes a series of data logging devices and point moisture measurement (PMM) sensors from SMT Research Ltd. to obtain the data associated with the dryout response of the deck. The point moisture measurement sensors are insulated probes that collect information including moisture, relative humidity, and temperature. To quantifiable determine how the material responds to increased moisture content and subsequent dryout, it is important to collect data from the sensors at various points within the timber. For this reason, the probes were embedded at three depths within the cross-laminated timber deck, and this is consistent within all panels as demonstrated in **Figure 7**.

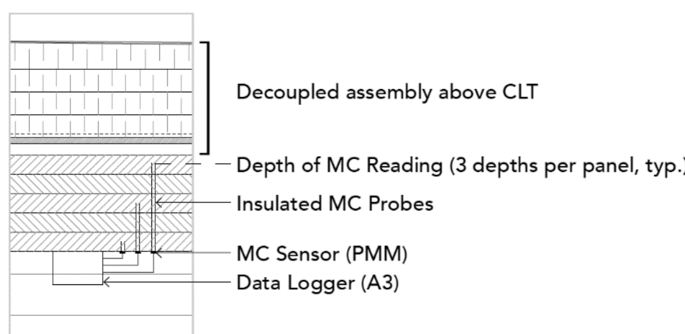

Figure 7: Typical Installation of Sensors at Center of Panel (Johns, 2023)

The three embedment depths and associated sensors are referred to within the analysis as "Interior Wood Layer," "Center Wood Layer", and "Exterior Wood Layer". Each sensors data is locally stored on their respective A3 data logging device for periodic downloads while on-site. In addition to the embedded equipment, additional sensors were installed on the interior and exterior of the test hut to obtain an equivalent baseline for comparisons and analyses. An important note is that point moisture measurement sensors gain readings by passing an electromagnetic wave between them, and with the available sensors on the market, there is a notable limitation whereas moisture content readings below 8.8% cannot be differentiated. Therefore, all readings of 8.8% or lower will appear as 8.8%. However, the majority of the relevant analysis occurs above 11%, therefore this will have minimal impact on the findings of this investigation.

3.0 Analysis

This section involves a qualitative analysis of sixteen months of readings data acquisition equipment, including a mould risk assessment and phased linear analyses of the dryout response. These analyses will establish trends between how the enclosure design affects the behaviour of the dryout and how incorrect design may impact occupant health.

Upon preliminary analysis, it was noted that panels 3 and 6 had faulty readings through excessively high readings and extended periods of missing data. These problems are both likely correlated to connectivity issues with the data acquisition system. Therefore panels 3 and 6 were omitted from the analysis.

3.1. Mould Risk Analysis

To assess the risk of mould growth, the average dryout rate will be analyzed through the use of simple linearization of dryout as previously explained in **Figure 3**. By initially determining the peak moisture content after installation of the panel into the test hut, we can identify any assemblies that are immediately at risk of mould growth, by determining whether or not the peak moisture content is above 15%.

After identifying which assemblies are vulnerable, using the average rate of change (slope) from the linear approximation of the function, the risk can be assessed in terms of time until the cross-laminated timber is deemed safe from mould growth which is simply below a moisture content of 15%.

The moisture content readings vary substantially, causing localized maxima and minima at arbitrary points in the readings due to the known error within the sensors. In similar experiments, moving averages are utilized in an attempt to normalize the data and minimize the impact outliers have without removing them entirely (Schmidt & Riggio, 2019). Therefore, the average moisture content readings were normalizing by calculating the average of the 24 hours before and after each reading, also known as a moving average of 49. An example of the effect of this calculation can be seen below in **Figure 8**, where moisture content is the dependent variable, and the hours since installation of sensors is the independent.

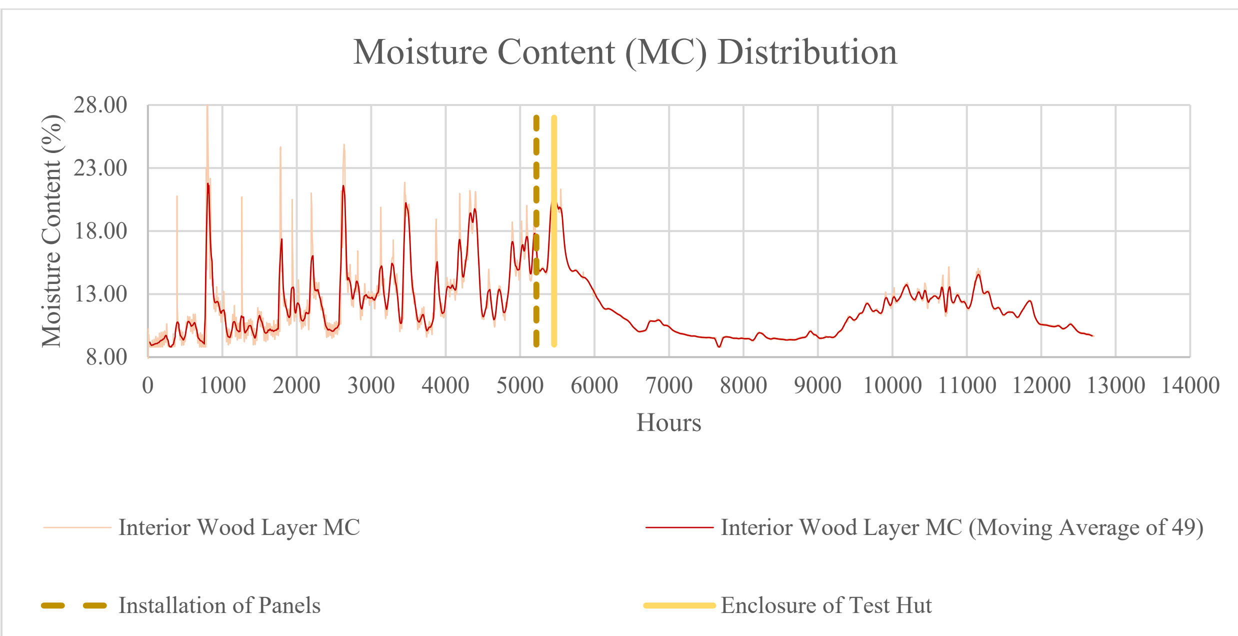

Figure 8: Moving Average of 49 on Sample Moisture Content Distribution

As can be seen in the readings, there are multiple observable peaks due to fluctuation in the electromagnetic wave and moisture migration. To calculate the average rate of dryout, the value of the peak moisture content in the initial peak after the enclosure of the test hut will be identified and recorded along with the time it occurs.

Additionally, for CLT to be classified as dry is widely accepted by manufacturers as less than 11% moisture content. However because the readings have high levels of variance, even with the moving average of 49, it was determined that a more definitive definition of dry in this analysis would be when the average reading at a given time was less than 11 for the following two weeks. This is to reduce the impact the localized minima may have on the dryout rate. Therefore once having identified the peak moisture content and associated time as well as the time at which the panel is dry, the average dryout can be calculated using the general slope formula. This calculation for the moisture content distribution of **Figure 8** can be seen below, and are plotted on **Figure 9**, where PMC = peak moisture content and DMC = dry moisture content:

$$slope = \frac{y_2 - y_1}{x_2 - x_1}$$

$$Rate\ of\ Dryout = \frac{PMC - DMC}{Time_{PMC} - Time_{DMC}}$$

$$Where\ PMC = 20.62\%\ @\ 5456\ hours, and\ DMC = 11.00\%\ at\ 6235\ hours$$

$$Rate\ of\ Dryout = \ -0.01235 \frac{\%}{Hour}\ or - 0.2964 \frac{\%}{Day}$$

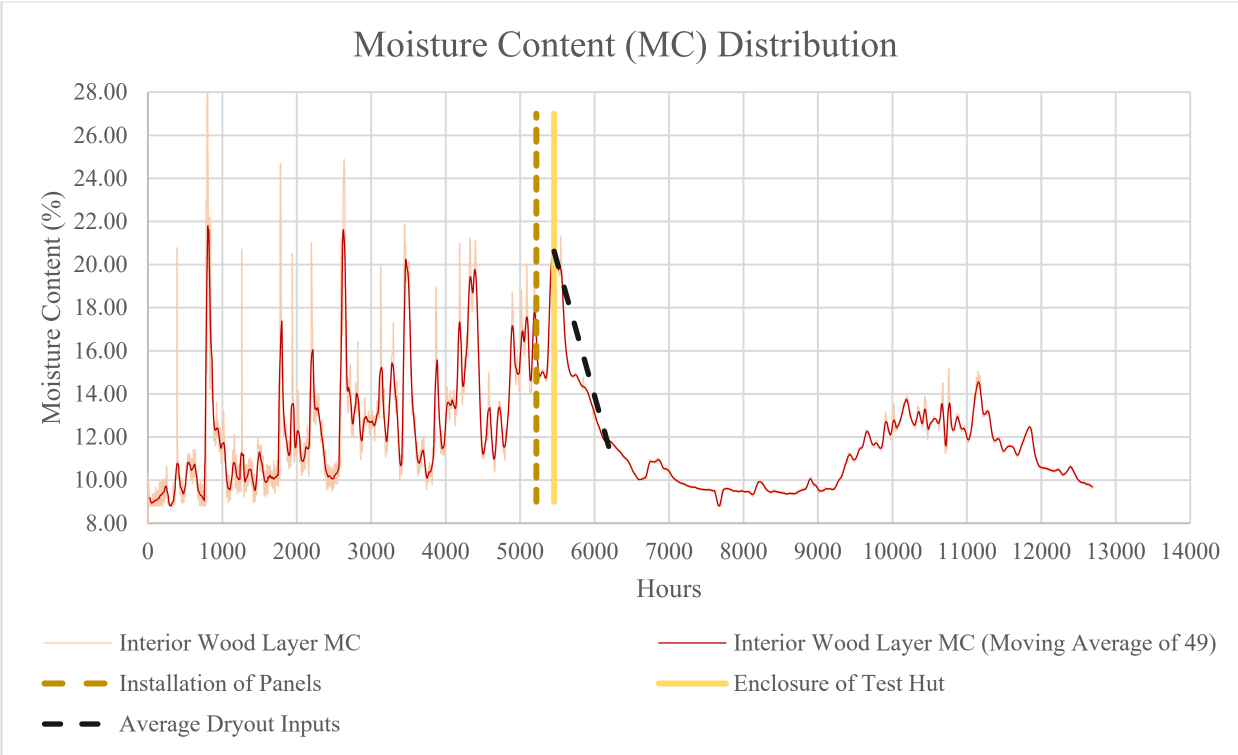

Figure 9: Average Dryout Sample Moisture Content Distribution

This analysis was completed for each layer of the set of panels. Using basic algebraic methods with peak moisture contents above 15% and the associated dryout rate, the amount of time can be determined until the panel is not at risk of mould growth by isolating for time in the following equation: $15\% = PMC - (Dry\ Out\ Rate) * time$

Using these analysis methods, **Table 2**, **Table 3**, and **Table 4** were developed to summarize the findings. The moisture content distributions used can be found the appendices. An important note is that the dryout rate cannot be calculated for panels that reached a peak moisture content of less than 11%, as they are already considered dry.

Table 2: Mould Risk Analysis of Exterior Layer

Panel	Peak Moisture Content (%)	Dryout Rate (%/Hr)	Dryout Rate (%/Day)	C.O.D (R^2)	Mould Risk (Hours)
1	15.67	-0.00873	-0.20958	0.92	76.94
2	15.03	-0.00263	-0.06321	0.08	10.31
3	Omitted from analysis.				
4	11.62	-0.00433	-0.10403	0.88	0
5	16.60	-0.00441	-0.10590	0.90	363.47
6	Omitted from analysis.				
7	12.57	-0.00425	-0.10200	0.89	0
8	19.42	-0.00474	-0.11378	0.88	933.24

Table 3: Mould Risk Analysis of Center Layer

Panel	Peak Moisture Content (%)	Dryout Rate (%/Hr)	Dryout Rate (%/Day)	C.O.D (R^2)	Mould Risk (Hours)
1	18.07	-0.02647	-0.63535	0.65	115.90
2	8.82	N/A	N/A	N/A	N/A
3	Omitted from analysis.				
4	10.79	N/A	N/A	N/A	N/A
5	14.81	-0.00677	-0.16247	0.86	0
6	Omitted from analysis.				
7	9.76	N/A	N/A	N/A	N/A
8	16.19	-0.00282	-0.06760	0.45	422.98

Table 4: Mould Risk Analysis of Interior Layer

Panel	Peak Moisture Content (%)	Dryout Rate (%/Hr)	Dryout Rate (%/Day)	C.O.D (R^2)	Mould Risk (Hours)
1	11.08	-0.00346	-0.08303	0.98	0
2	8.80	N/A	N/A	N/A	N/A
3	Omitted from analysis.				
4	8.94	N/A	N/A	N/A	N/A
5	14.43	-0.01308	-0.31381	0.97	0
6	Omitted from analysis.				
7	13.30	-0.00824	-0.19767	0.92	0
8	17.50	-0.00190	-0.04572	0.90	1312.23

Based on these findings, multiple assemblies were found to be at risk of mould growth. The least concerning of these appears to be Panel 2, where it is only found to be at risk for 10 hours and based on only the exterior sensor. Secondly, Panel 1 was found to be at risk based on the exterior and center layer sensors but appear to dry out below 15% within approximately 5 days. Panel 5 is at risk of mould growth for over 15 days based on the center layer sensor and may be of serious concern. Panel 8 is at serious risk of mould growth based on the readings of all sensors. Based on the dryout rate, the interior panel would require over 54 days to no longer be in the risk zone for mould growth, which is a serious concern for occupant comfort.

3.2. Phased Linear Analyses

A similar analysis was conducted to Section 3.1, however further analyzing the dryout response in more precise phases. Rather than taking dryout rate from peak moisture content to dry moisture content, three distinct phases are analyzed where applicable to compare the initial dryout rate (20.0% to 15.0%), the intermediate dryout rate (15.0% to 11.0%), and the final dryout rate (11% to 8.8%). An example on the sample moisture distribution can be found below in **Figure 10**.

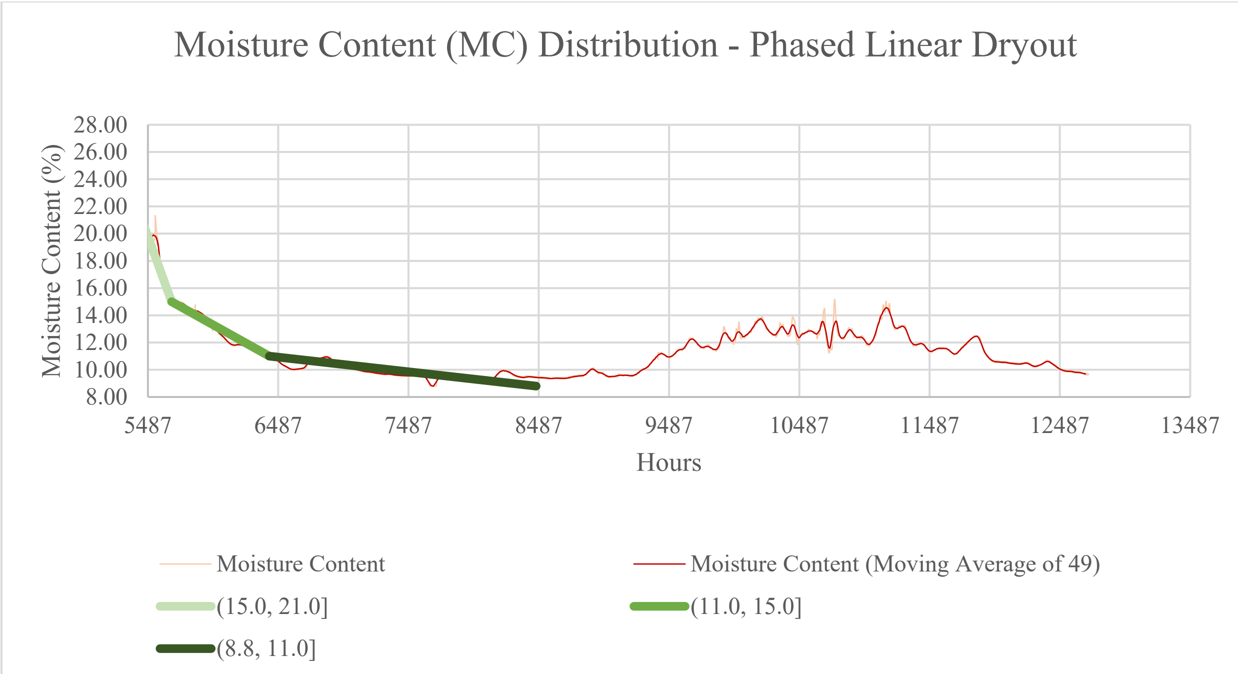

Figure 10: Phased Linear Analysis of Sample Moisture Content Distribution

Whereas the peak moisture content doesn't reach the upper bound of one the phases, the peak moisture content will be taken in lieu. For example, if the peak moisture content of a sample is 14.3, the intermediate dryout rate will be calculated from 14.3% to 11.0% and the high dryout rate will be non-applicable. **Table 5**, **Table 6**, and **Table 7** summarize the findings from this phase of the analysis:

Table 5: Phased Linear Analysis of Exterior Layer

Panel	High Dryout Rate (%/Day)	Intermediate Dryout Rate (%/Day)	Low Dryout Rate (%/Day)
1	-0.5972	-0.1391	-0.0258
2	-0.0271	-0.0638	# N/A
3		Omitted from analysis.	
4	N/A	-0.0414	-0.0325
5	-0.7547	-0.1039	-0.0086
6		Omitted from analysis.	
7	N/A	-0.0748	-0.0080
8	-0.2154	-0.0617	-0.0104

Table 6: Phased Linear Analysis of Center Layer

Panel	High Dryout Rate (%/Day)	Intermediate Dryout Rate (%/Day)	Low Dryout Rate (%/Day)
1	-1.47	-0.25	-0.15
2	N/A	N/A	0.00
3		Omitted from analysis.	
4	N/A	N/A	-0.17
5	N/A	-0.13	-0.01
6		Omitted from analysis.	
7	N/A	N/A	-0.05
8	-0.54	-0.20	-0.01

Table 7: Phased Linear Analysis of Interior Layer

Panel	High Dryout Rate (%/Day)	Intermediate Dryout Rate (%/Day)	Low Dryout Rate (%/Day)
1	0.00	-0.27	-0.01
2	N/A	N/A	N/A
3		Omitted from analysis.	
4	N/A	N/A	-0.02
5	N/A	N/A	-0.03
6		Omitted from analysis.	
7	N/A	-0.08	-0.04
8	-0.04	-0.05	-0.04

Using the phased values and the average dryout values calculated in Section 3.1, the peak moisture content is plotted against the dryout rate for all panels to serve as a method for visually establishing trends. **Figure 11**, **Figure 12**, and **Figure 13** demonstrate these plots showing the average dryout and peak moisture content or the exterior, center, and interior layer respectively. The plots for high, intermediate, and low dryout rates can be found in Appendix F, G, and H.

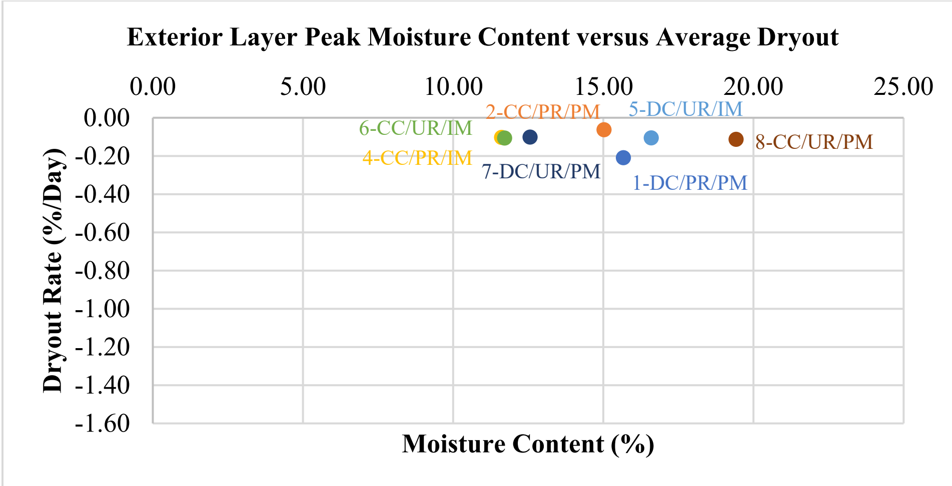

Figure 11: Exterior Layer Peak Moisture Content versus Average Dryout

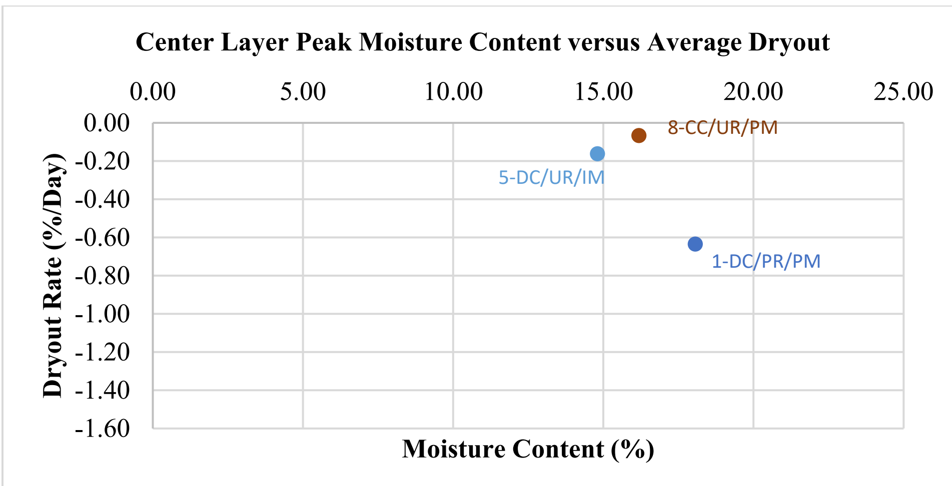

Figure 12: Center Layer Peak Moisture Content versus Average Dryout

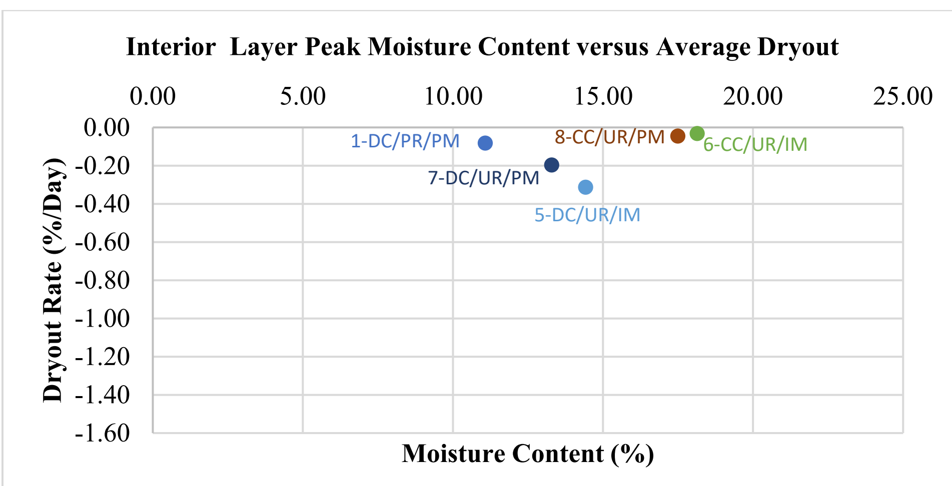

Figure 13: Interior Layer Peak Moisture Content versus Average Dryout

3.3. Results

The results of the mould risk assessment can provide qualitative observations that can prove to be beneficial in similar applications. Although panel 1 and 2 reached a moisture content of above 15%, both were protected with permeable membranes. The protection helped reduce the peak moisture from rising to higher levels, and the permeable membrane promoted rapid dryout on the exterior as demonstrated by the lack of moisture migrating through the assembly into the center and interior layers of these assemblies. Panel 5 and 8 both demonstrate how the unprotected assemblies were subject to much higher peak moisture contents and demonstrated that even with permeable membranes or decoupled systems, the moisture is unable to dryout fast enough to prevent the risk of mould growth.

The phased linear analyses demonstrated various trends that occurred. Firstly, the analysis additionally confirmed that unprotected assemblies experienced the highest peak moisture content, demonstrating that regardless of if the membrane was protected with a permeable or impermeable membrane, any form of membrane drastically limited moisture from migrating into the CLT deck. Secondly, although not as critical as unprotected assemblies, permeable membranes did experience higher moisture contents than impermeable membranes did during the panel exposure period. In most cases, permeable membranes promoted more rapid dryout. With that said, the permeable membrane had a similar effect on the performance as decoupling, although it is known that both practices are intended to promote airflow, it appears as though the directionality of dryout had relatively limited effect on the dryout response as decoupling promotes lateral airflow between panels whereas the permeable membrane promotes airflow to the exterior. A CC/PM had relatively similar performance compared to DC/IM, whereas DC/PM generally experienced higher moisture content but faster dryout. Additionally, it was noted that the CC/IM assembly had one of the highest moisture contents and lowest dryout speed.

In summary, promoting dryout of the assemblies though the use of permeable membranes where applicable assisted in limiting moisture migration. Additionally, mass timber in enclosure assemblies that are subject to high levels moisture for extended periods of time are at serious risk of mould growth and potential rot. Although practices such as ventilation through decoupling were assumed to impact the performance more positively than the results demonstrated, and there was still potential mould growth when utilizing these practices, it is important to note that promoting airflow through decoupling still generally increased the dryout rate after the assembly was enclosed compared to coupled assemblies even without the installation of explicit ventilation. Nevertheless, based on these findings, it is recommended that timber structures be protected as soon as possible from moisture, as promoting dryout through ventilation after the wood is quite saturated does not appear to have enough of an impact to prevent negative implications.

4.0 Conclusion

In conclusion, this investigation is extremely valuable to understanding how construction practices and enclosure design is critical for timber structures. Unlike other building materials where incorrect application of enclosure design may result in structural and/or performance failures, mass timber enclosure failures can also be detrimental to occupant health as a result of mould growth. Throughout this report, fundamental building science principles were explored, primarily the role of ventilation and permeability of membranes on dryout response.

In conclusion, the analysis and subsequent report have provided numerous conclusions that reinforce our current understanding of the fundamental knowledge for modern day enclosure design. In addition to further proving information priorly taken as factual, the results have demonstrated that the construction practices not only need to meet the prescribed objectives given on engineering drawings and details, but that there needs to be understanding of the purpose of control layers within the enclosure to guarantee the installation is done properly and on-time. This was ultimately demonstrated through the delayed application of a protective membrane to the timber deck in four of the eight assemblies, as purely installing a membrane and promoting ventilation after the timber has already been saturated did not mitigate the high moisture content fast enough. In real-world application, the misunderstanding of the importance for proper enclosure design including protective membranes will directly negate the structure to have sufficient air quality and environmental conditions that required for occupants or inhabitants in the modern day.

5.0 References

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APPENDIX A: Panel 1 Moisture Content Distributions

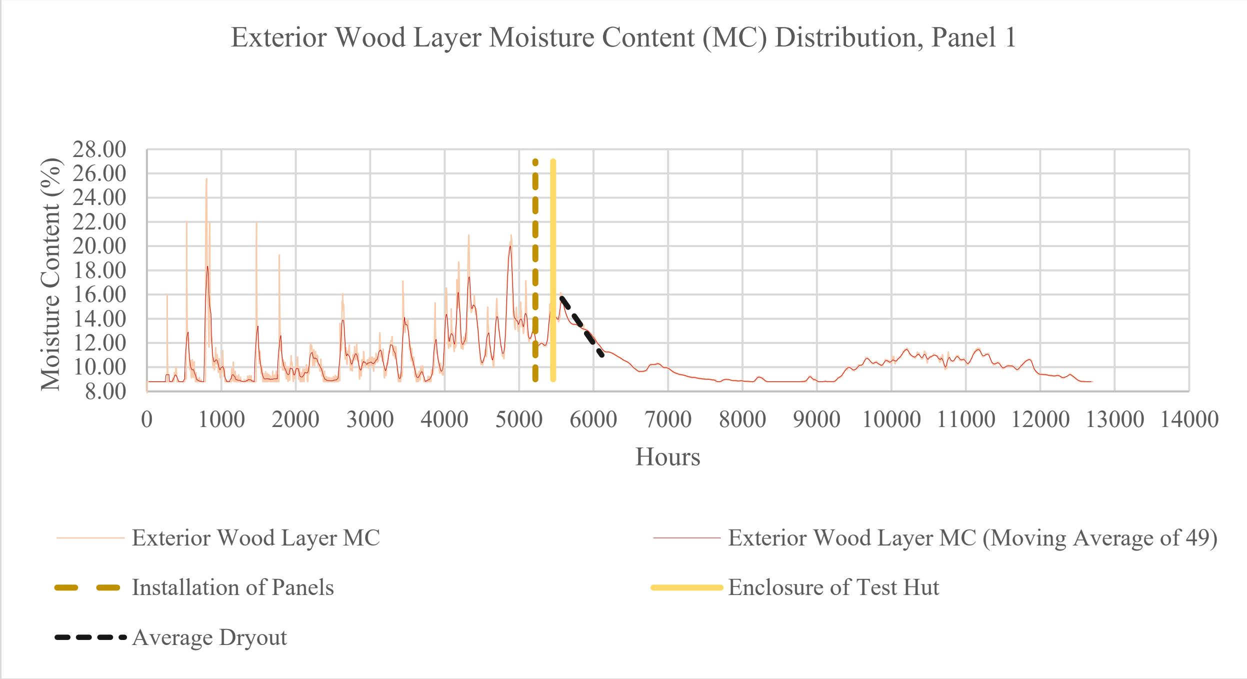

Figure 14: Exterior Wood Layer Moisture Content (MC) Distribution, Panel 1

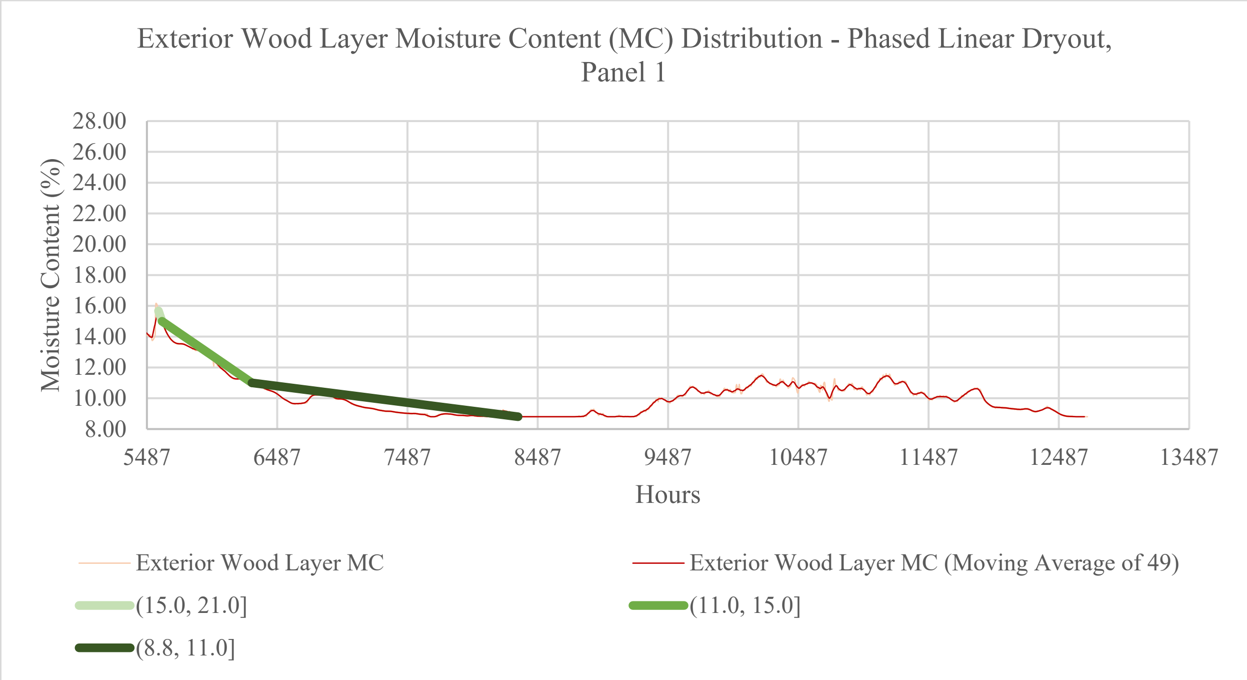

Figure 15: Exterior Wood Layer Moisture Content (MC) Distribution - Phased Linear Dryout, Panel 1

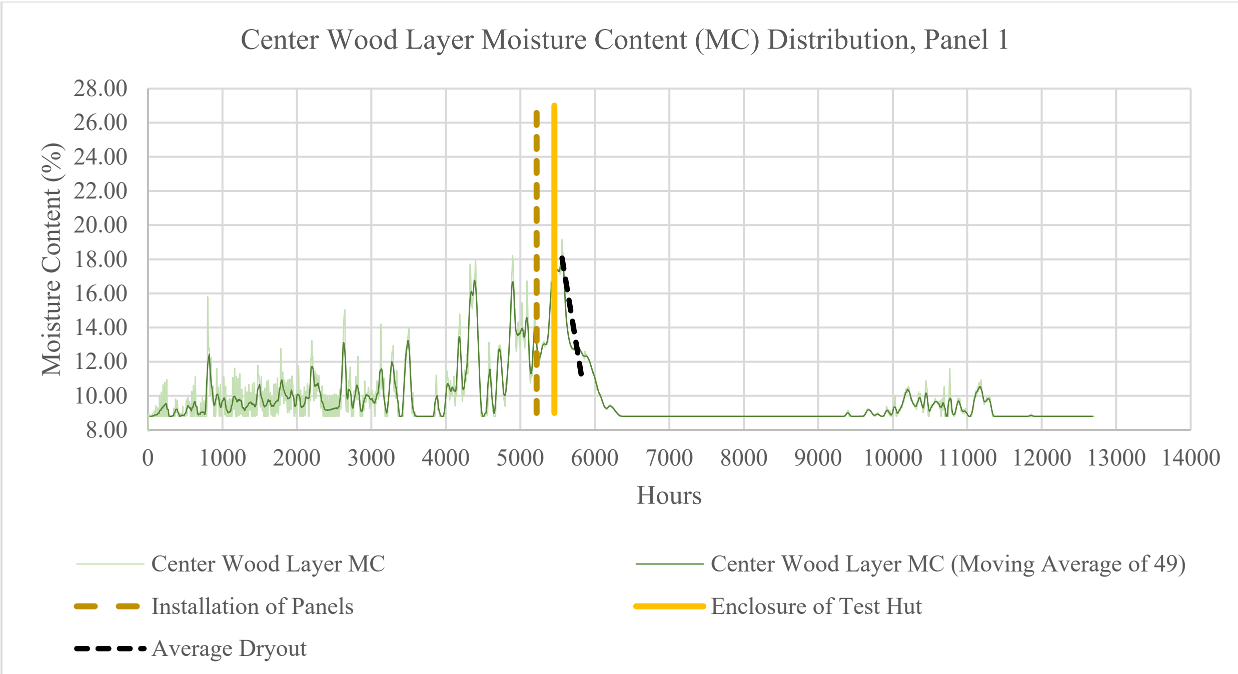

Figure 16: Center Wood Layer Moisture Content (MC) Distribution, Panel 1

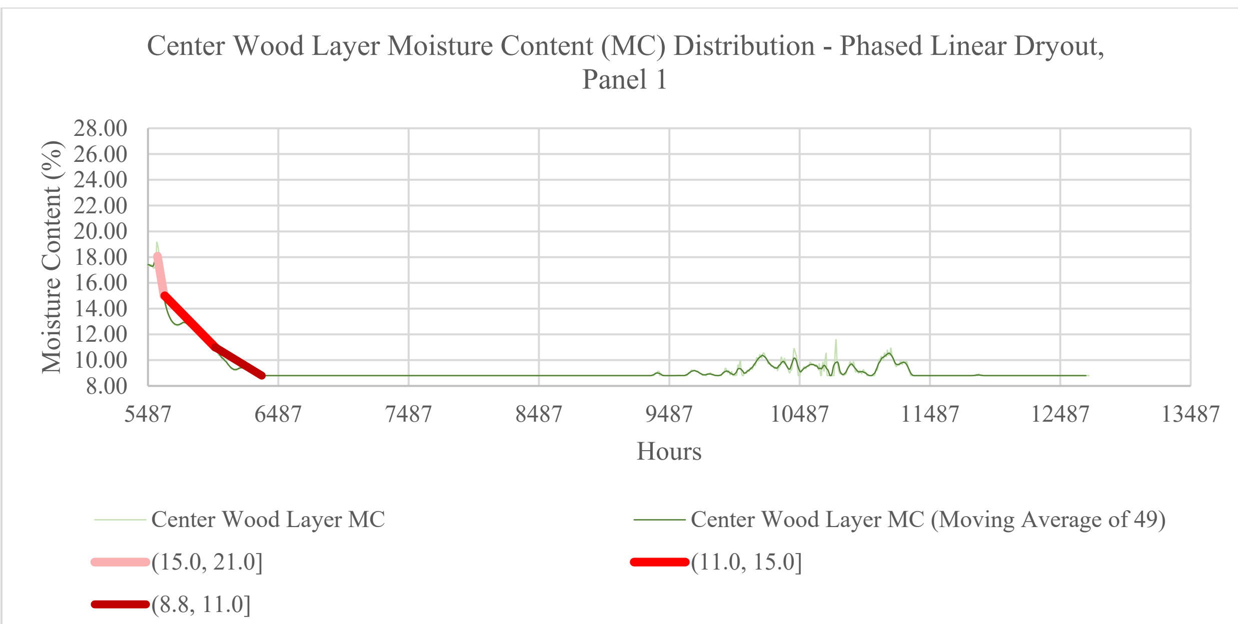

Figure 17: Center Wood Layer Moisture Content (MC) Distribution - Phased Linear Dryout, Panel 1

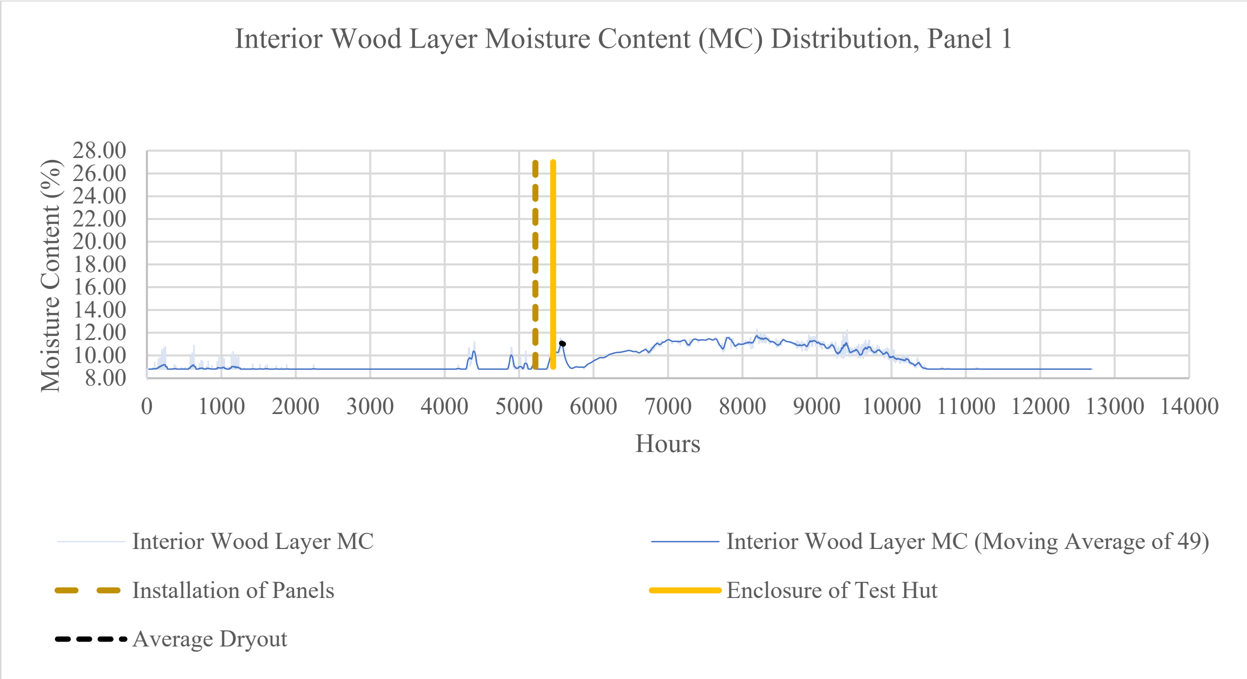

Figure 18: Interior Wood Layer Moisture Content (MC) Distribution, Panel 1

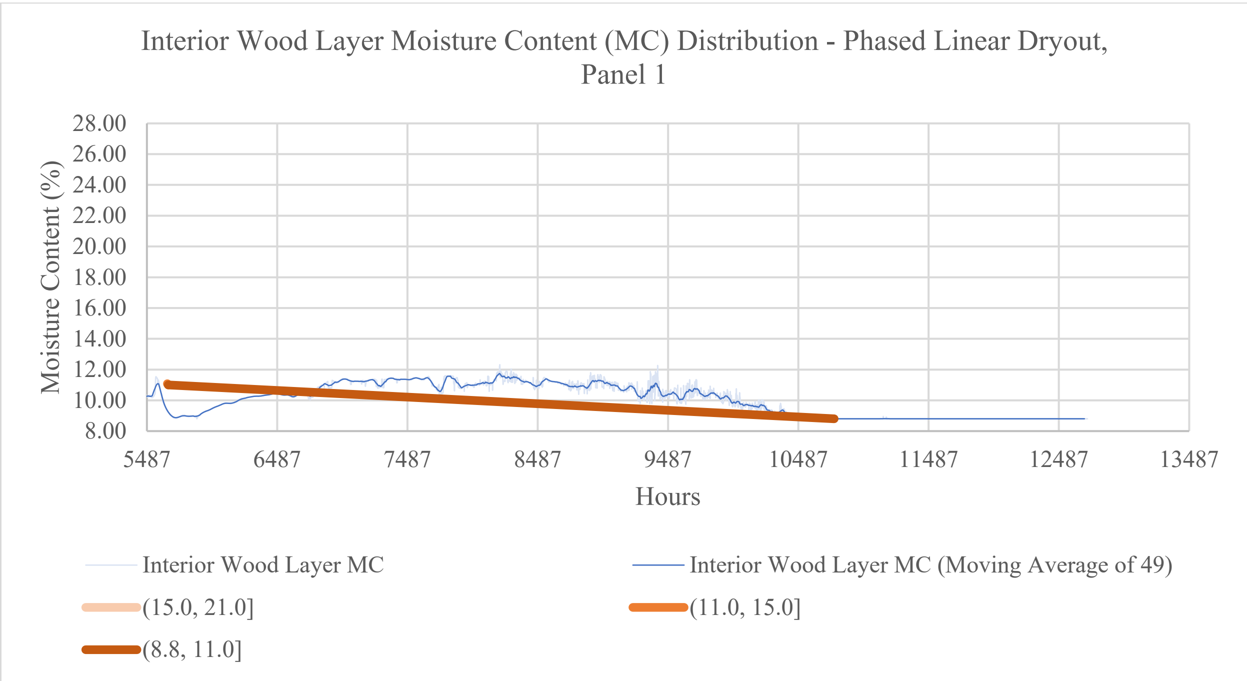

Figure 19: Interior Wood Layer Moisture Content (MC) Distribution - Phased Linear Dryout, Panel 1

APPENDIX B: Panel 2 Moisture Content Distributions

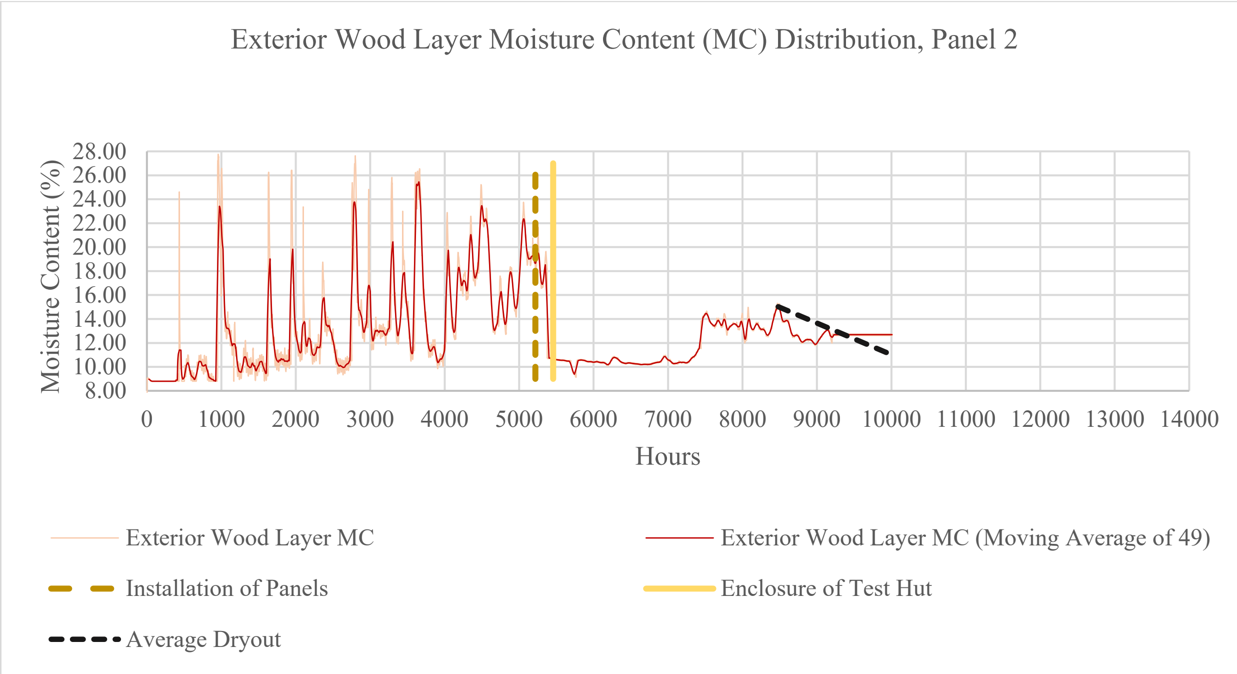

Figure 20: Exterior Wood Layer Moisture Content (MC) Distribution, Panel 2

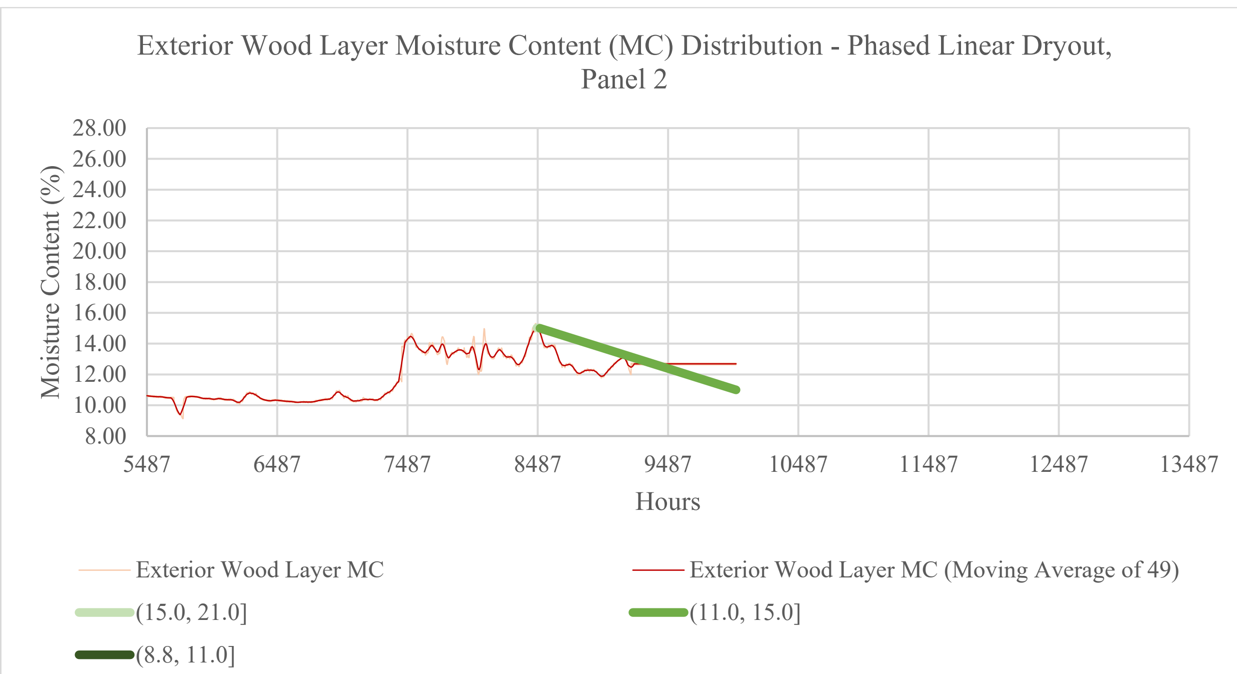

Figure 21: Exterior Wood Layer Moisture Content (MC) Distribution - Phased Linear Dryout, Panel 2

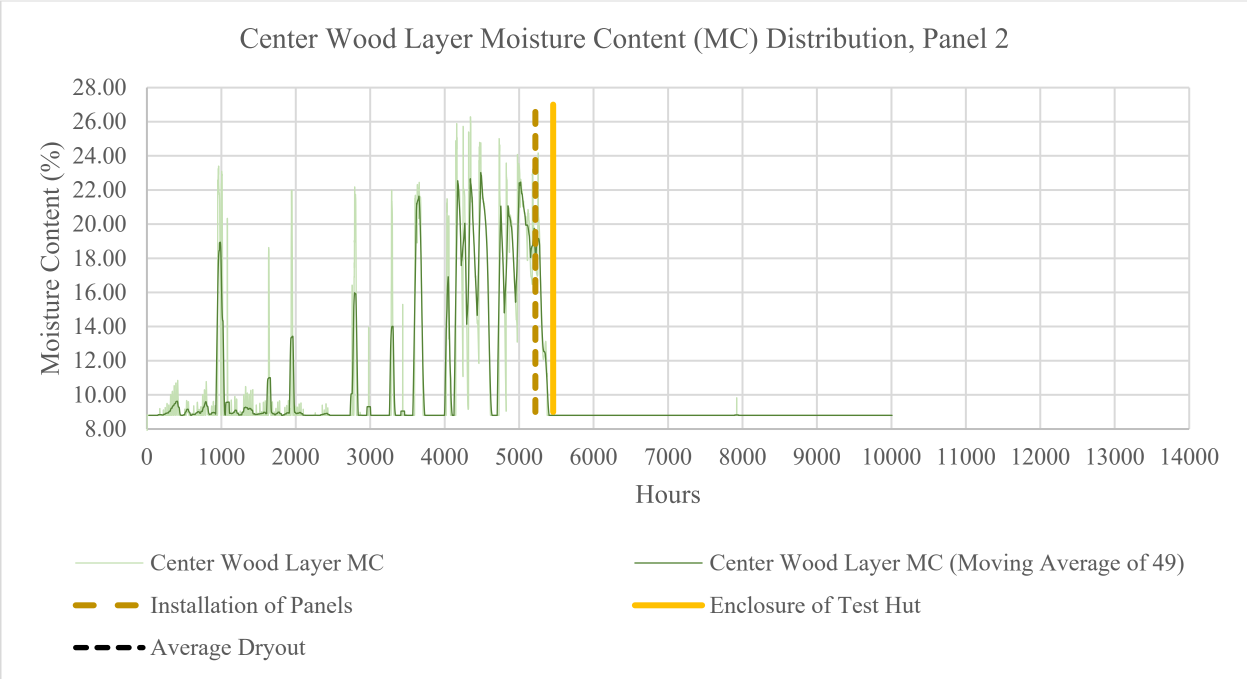

Figure 22: Center Wood Layer Moisture Content (MC) Distribution, Panel 2

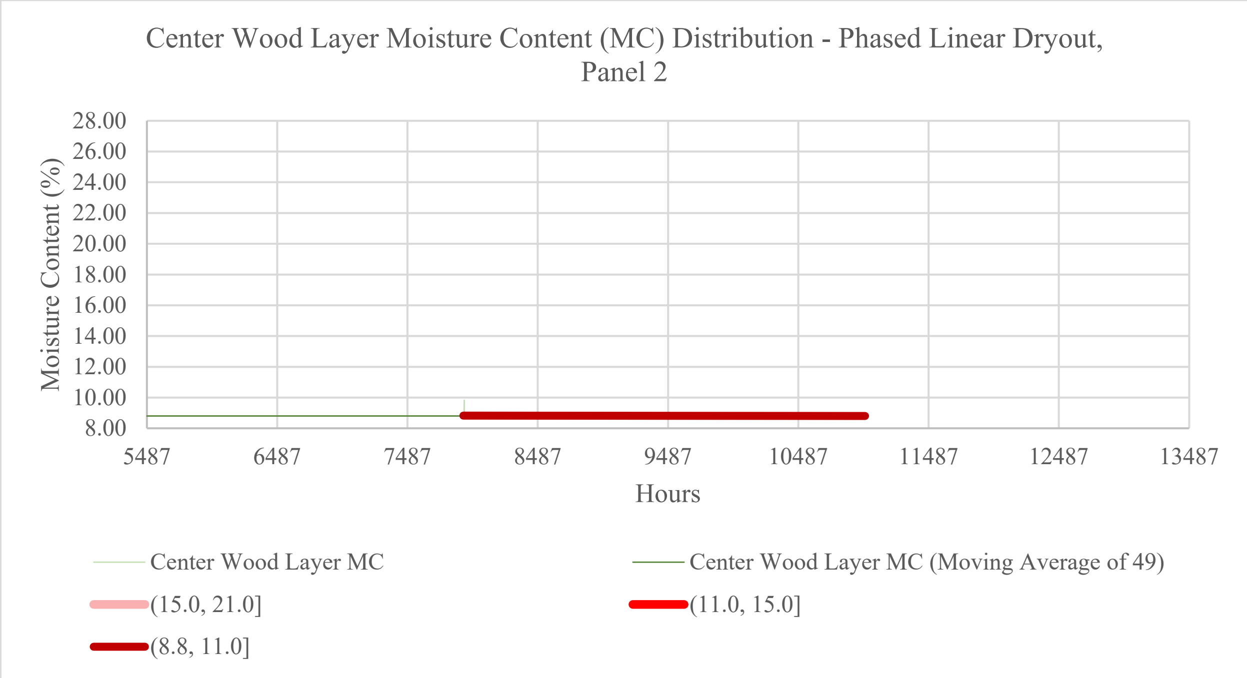

Figure 23: Center Wood Layer Moisture Content (MC) Distribution - Phased Linear Dryout, Panel 2

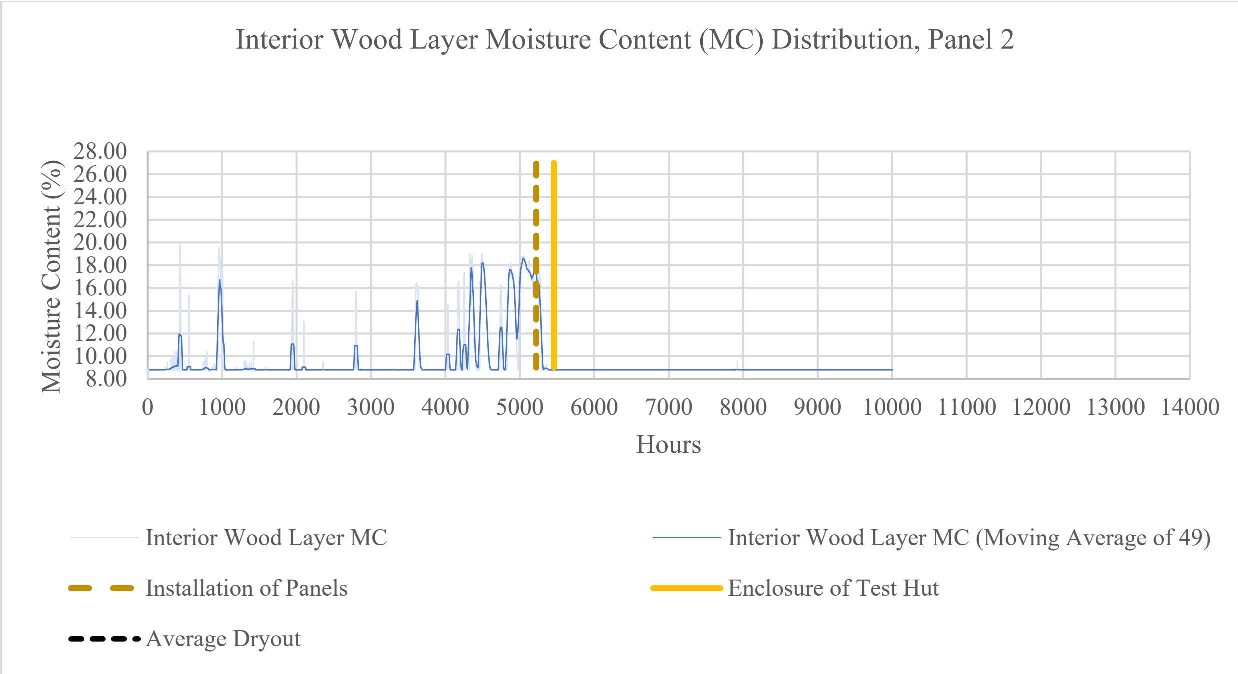

Figure 24: Interior Wood Layer Moisture Content (MC) Distribution, Panel 2

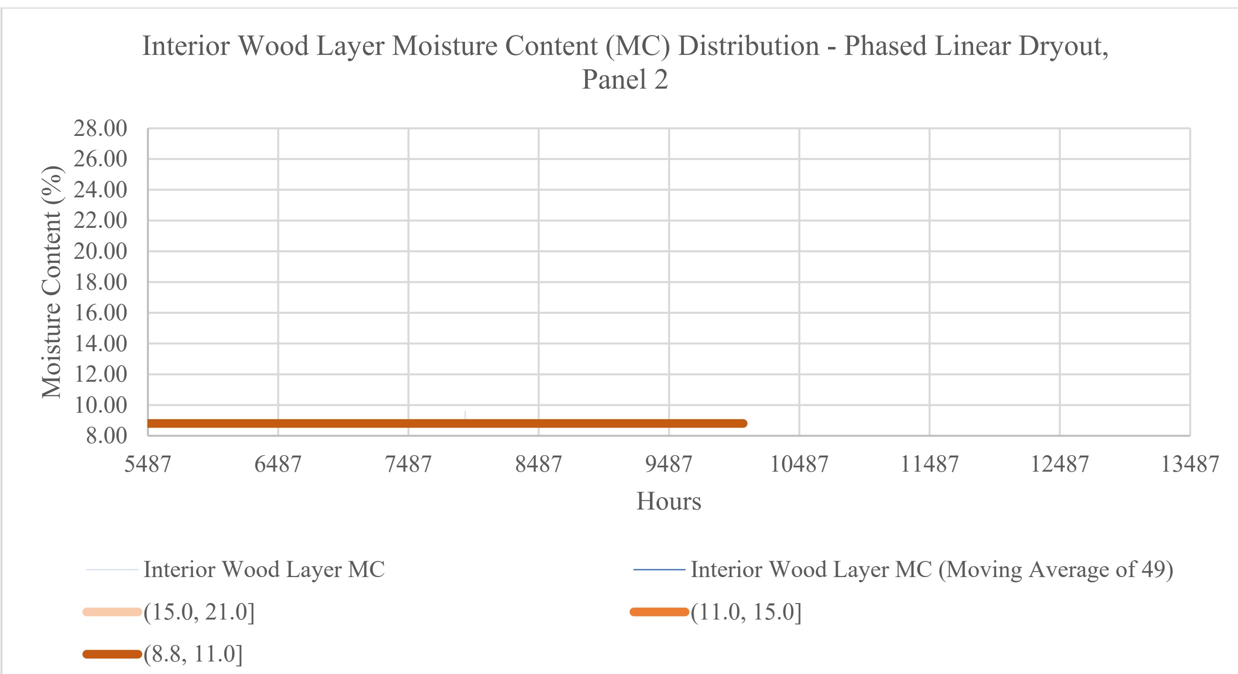

Figure 25: Interior Wood Layer Moisture Content (MC) Distribution - Phased Linear Dryout, Panel 2

APPENDIX C: Panel 4 Moisture Content Distributions

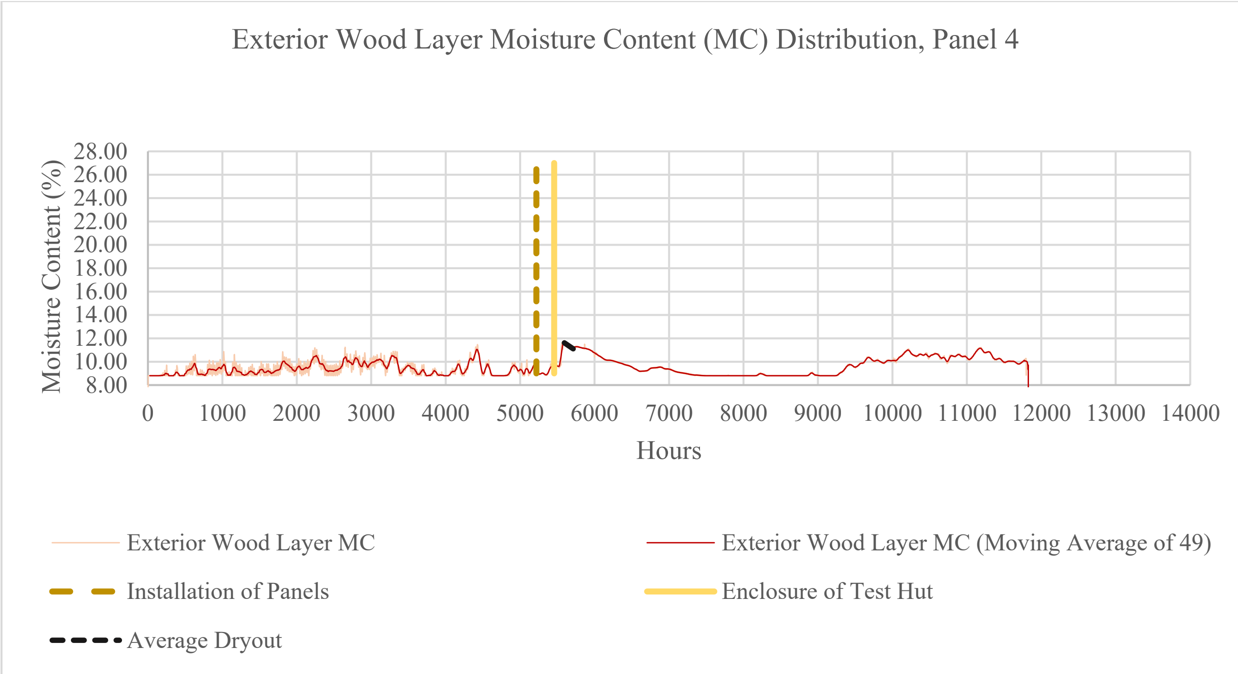

Figure 26: Exterior Wood Layer Moisture Content (MC) Distribution, Panel 4

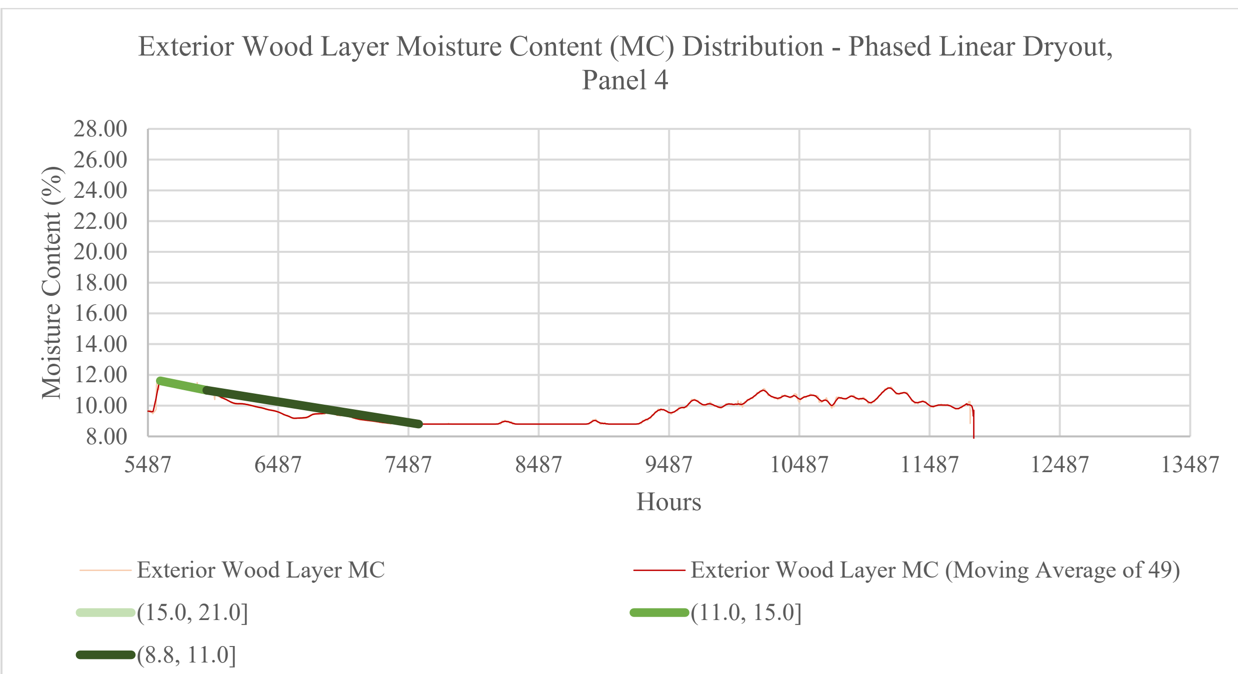

Figure 27: Exterior Wood Layer Moisture Content (MC) Distribution - Phased Linear Dryout, Panel 4

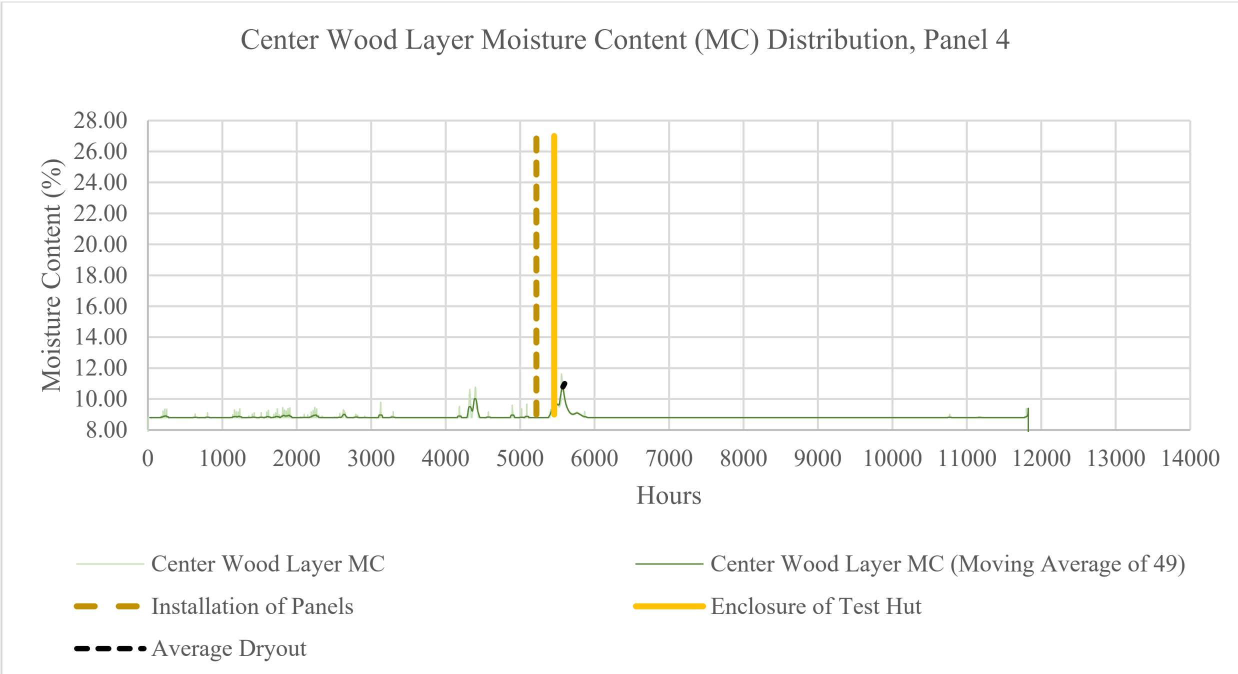

Figure 28: Center Wood Layer Moisture Content (MC) Distribution, Panel 4

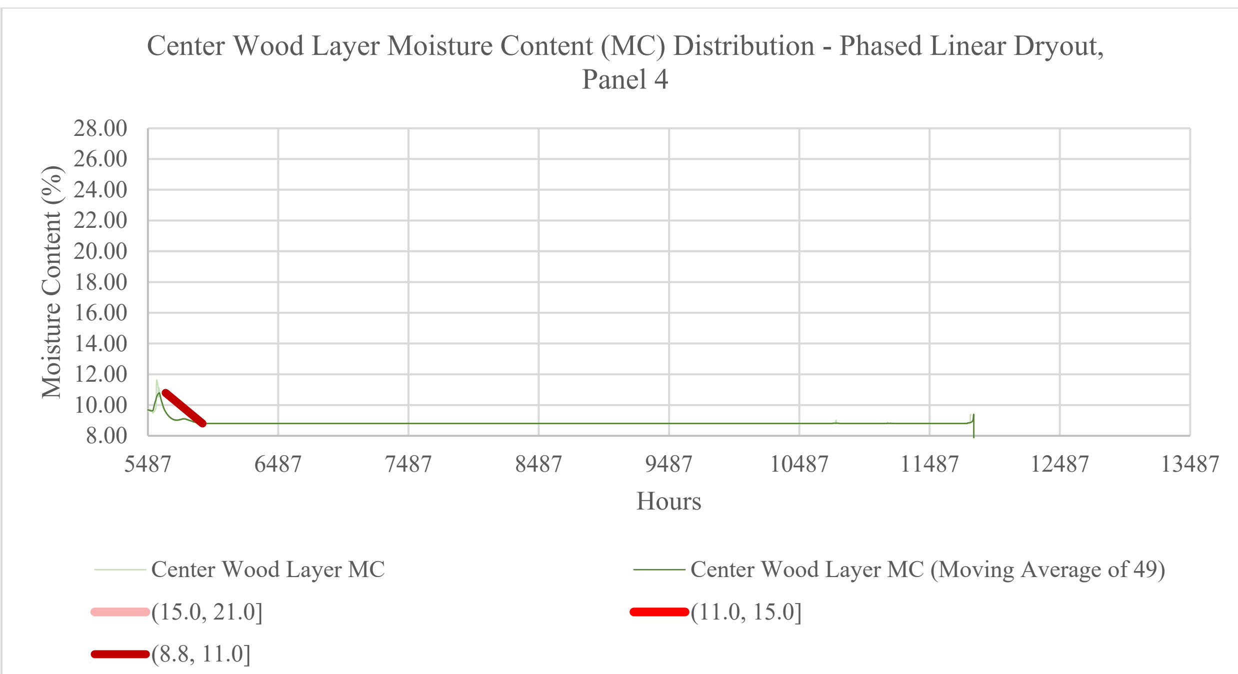

Figure 29: Center Wood Layer Moisture Content (MC) Distribution - Phased Linear Dryout, Panel 4

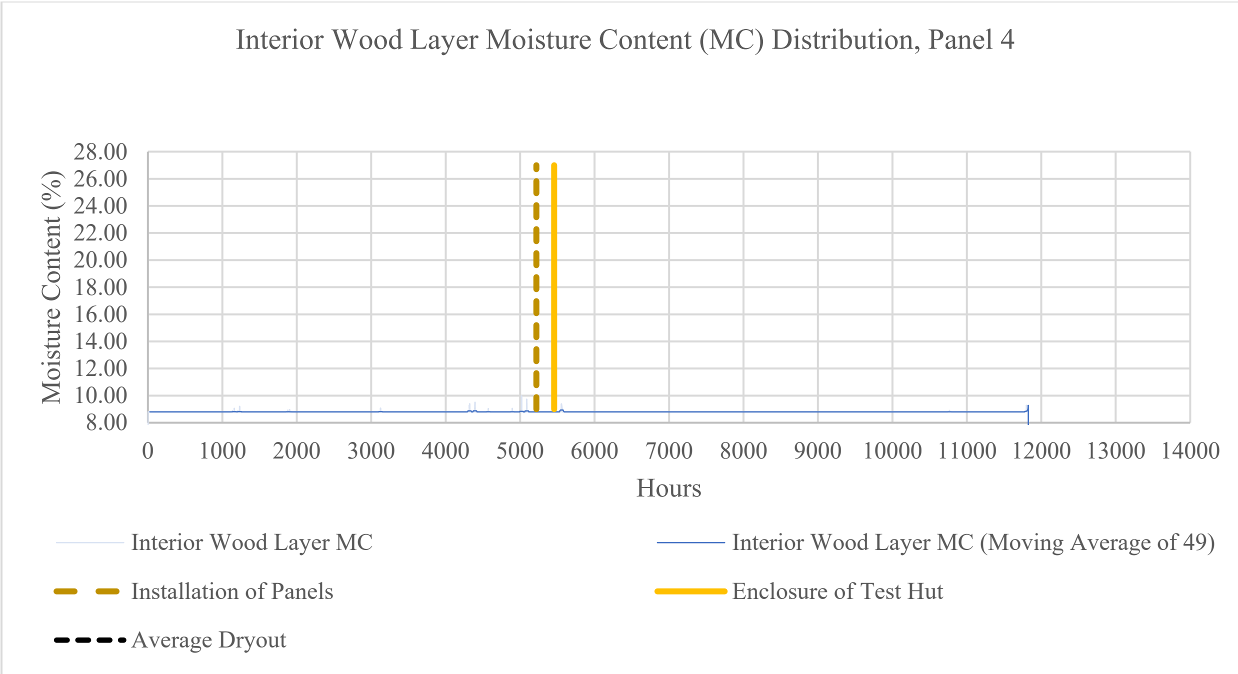

Figure 30: Interior Wood Layer Moisture Content (MC) Distribution, Panel 4

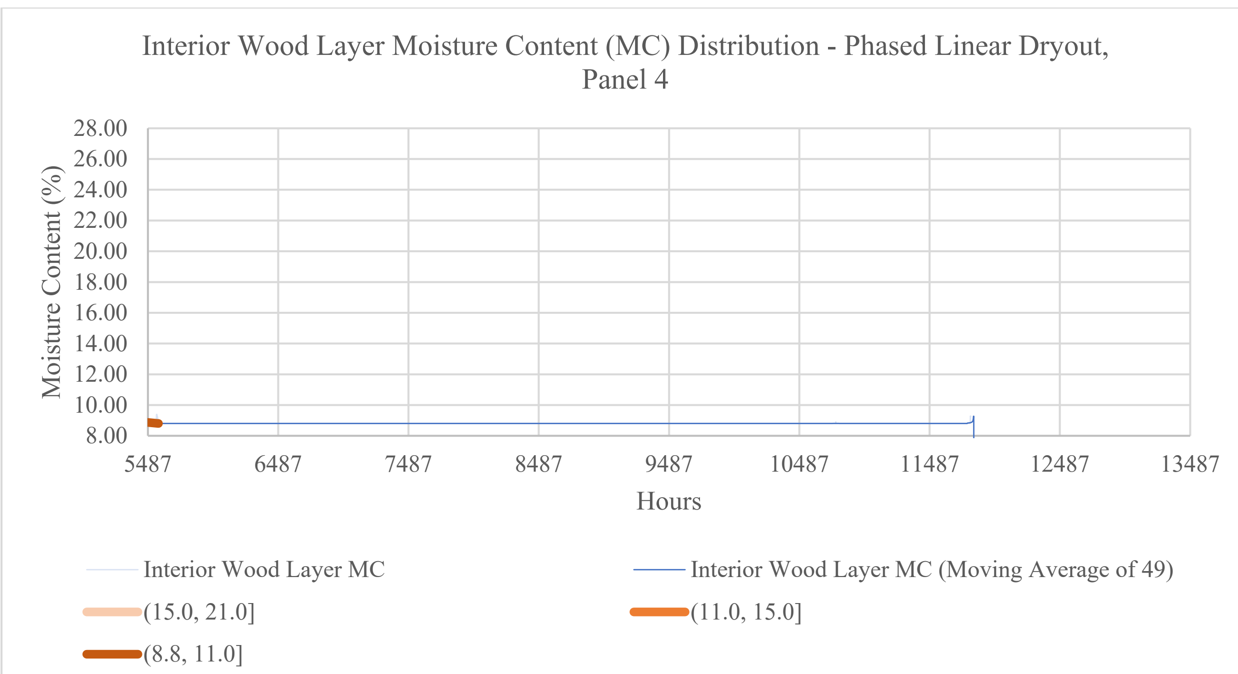

Figure 31: Interior Wood Layer Moisture Content (MC) Distribution - Phased Linear Dryout, Panel 4

APPENDIX D: Panel 5 Moisture Content Distributions

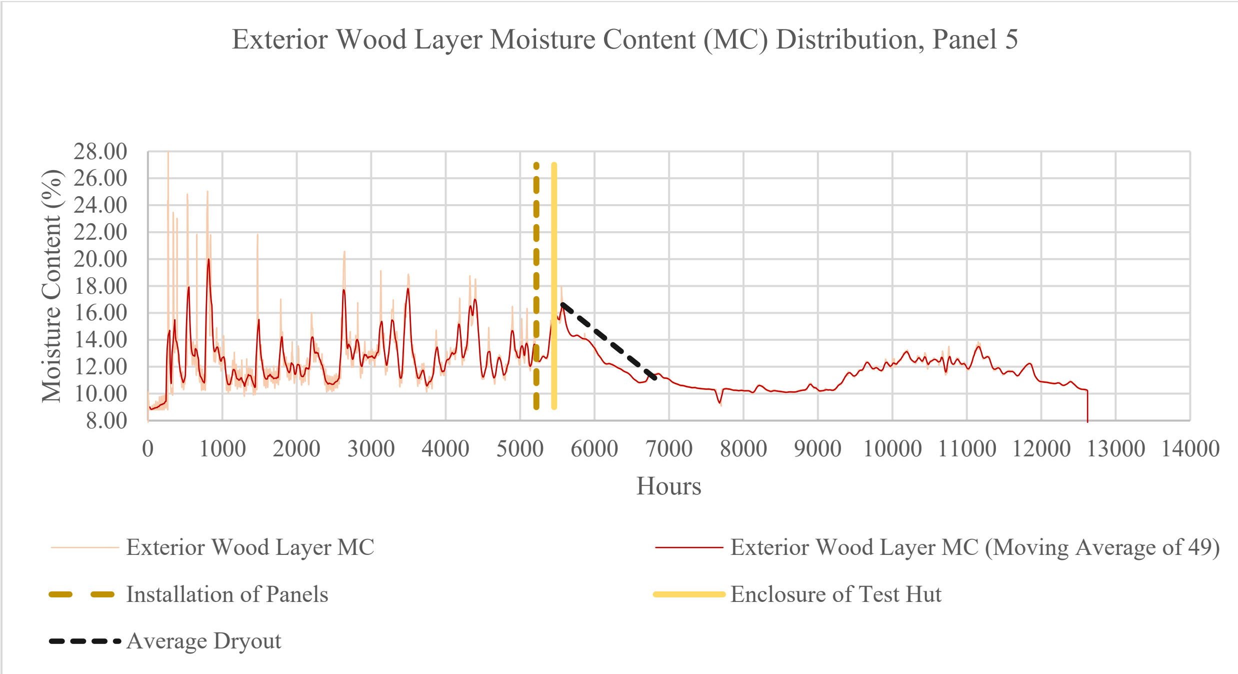

Figure 32: Exterior Wood Layer Moisture Content (MC) Distribution, Panel 5

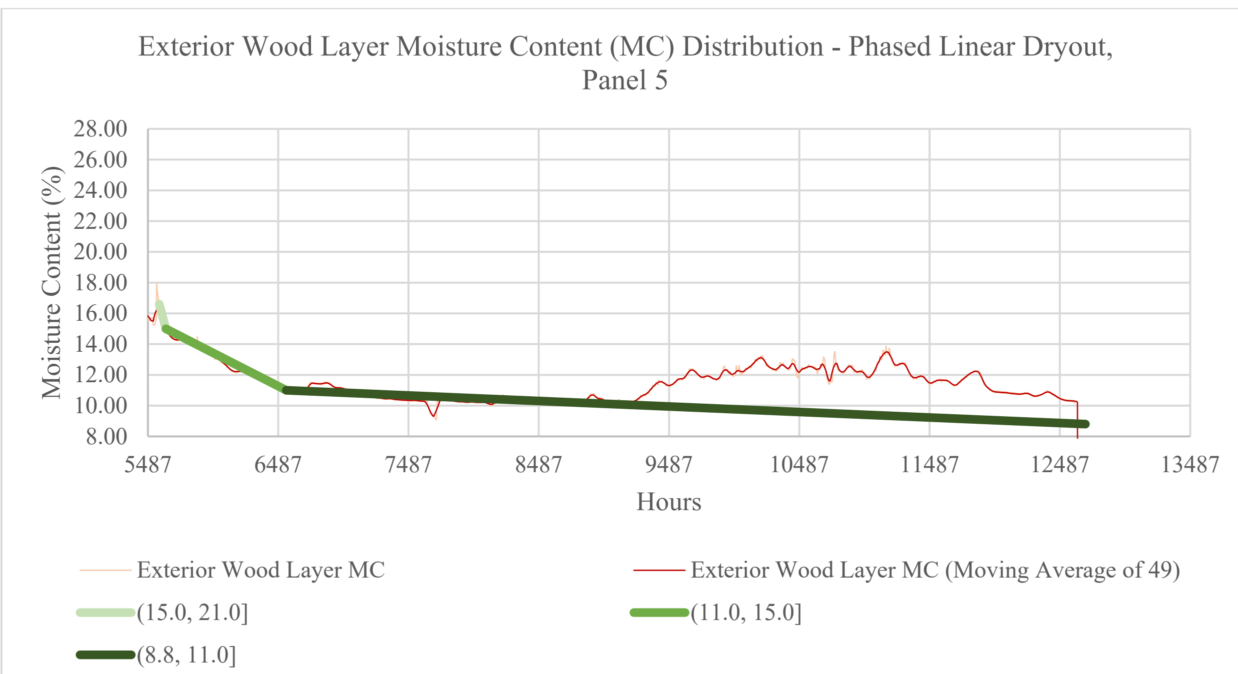

Figure 33: Exterior Wood Layer Moisture Content (MC) Distribution - Phased Linear Dryout, Panel 5

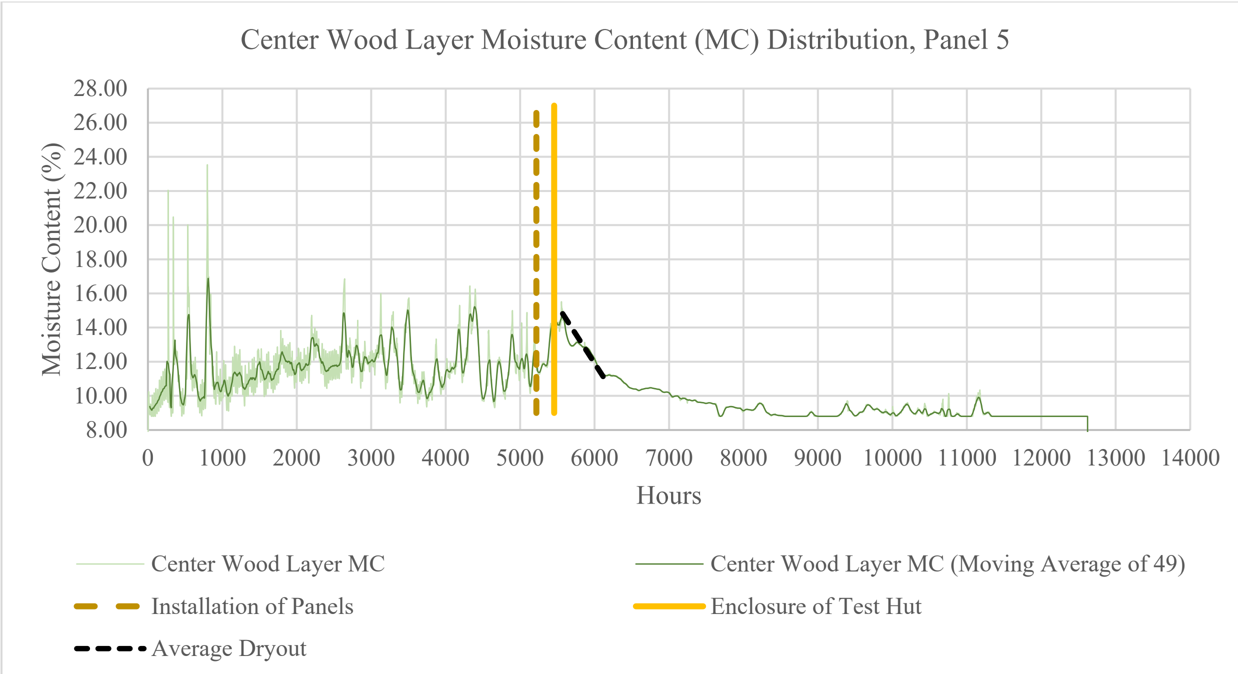

Figure 34: Center Wood Layer Moisture Content (MC) Distribution, Panel 5

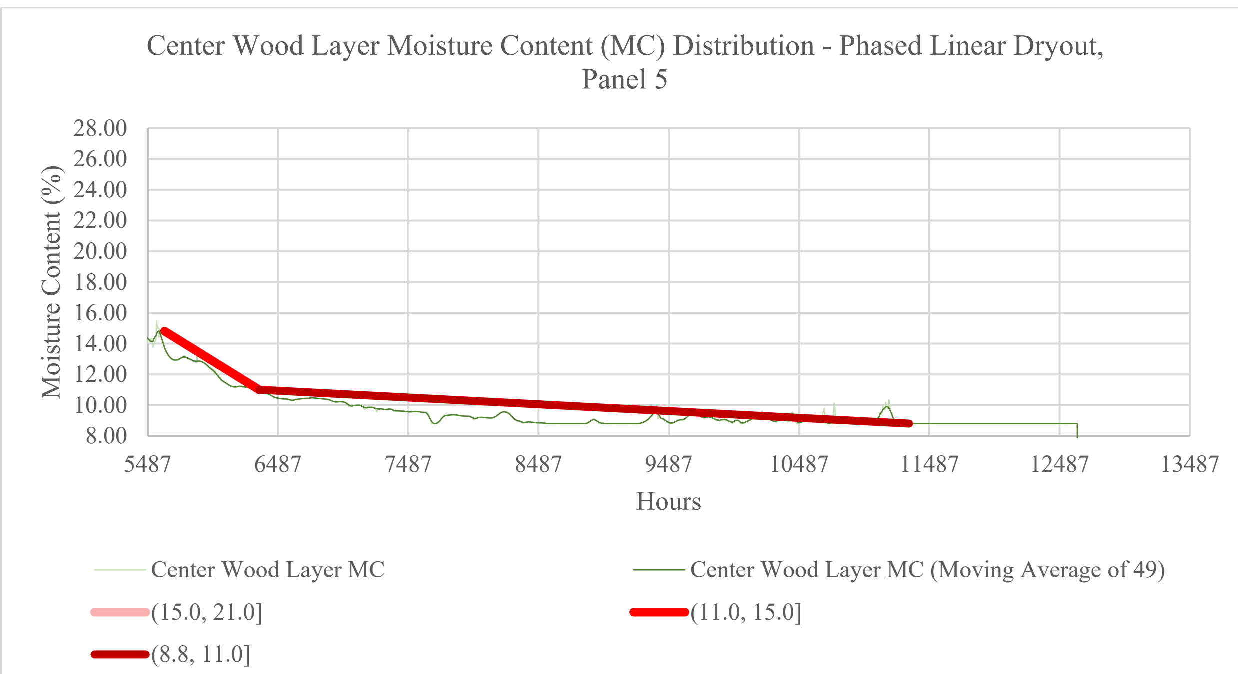

Figure 35: Center Wood Layer Moisture Content (MC) Distribution - Phased Linear Dryout, Panel 5

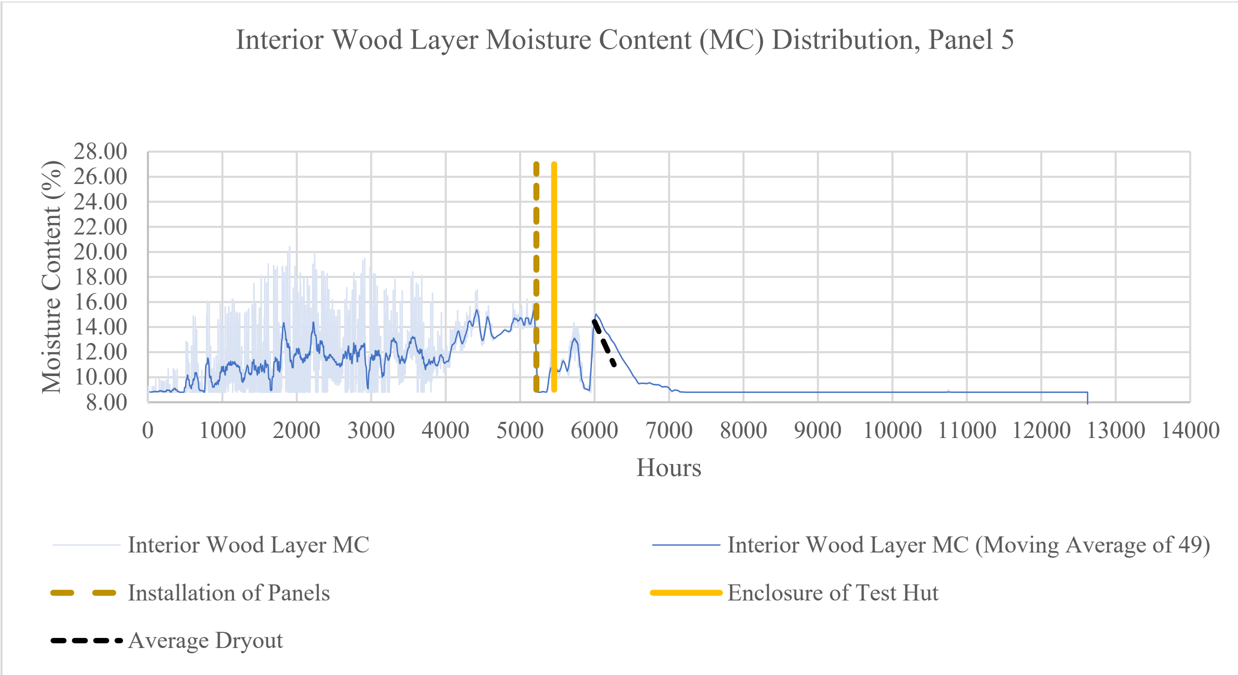

Figure 36: Interior Wood Layer Moisture Content (MC) Distribution, Panel 5

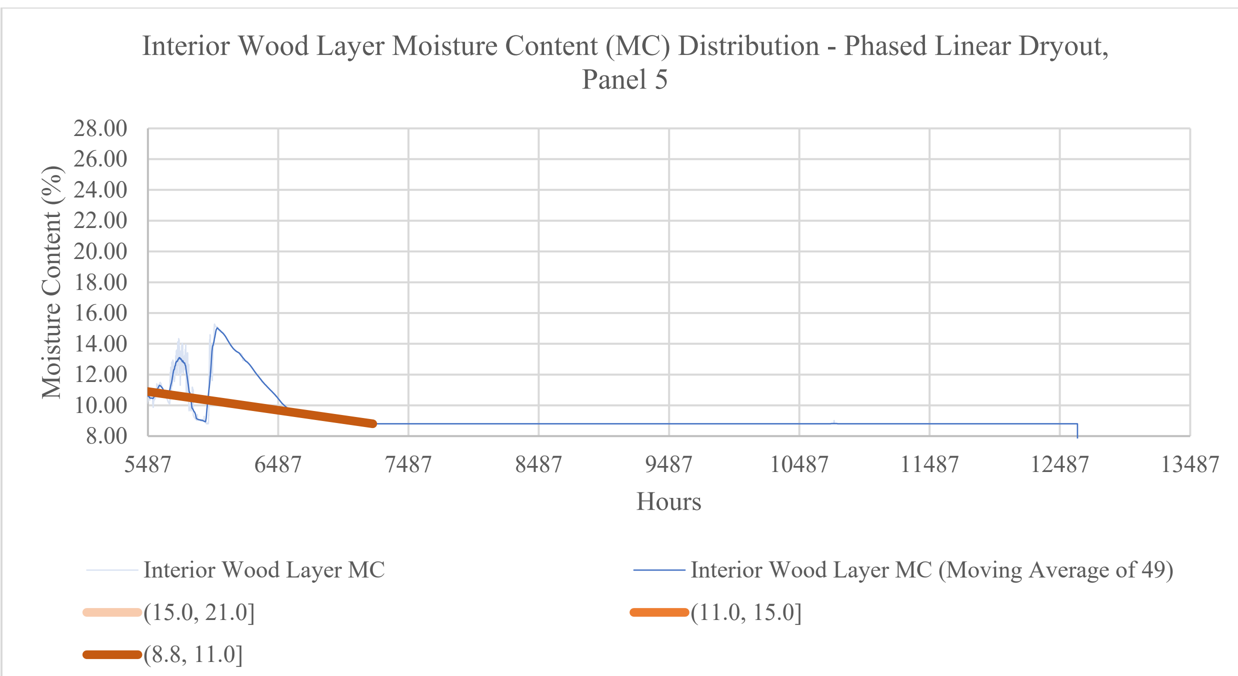

Figure 37: Interior Wood Layer Moisture Content (MC) Distribution - Phased Linear Dryout, Panel 5

APPENDIX E: Panel 7 Moisture Content Distributions

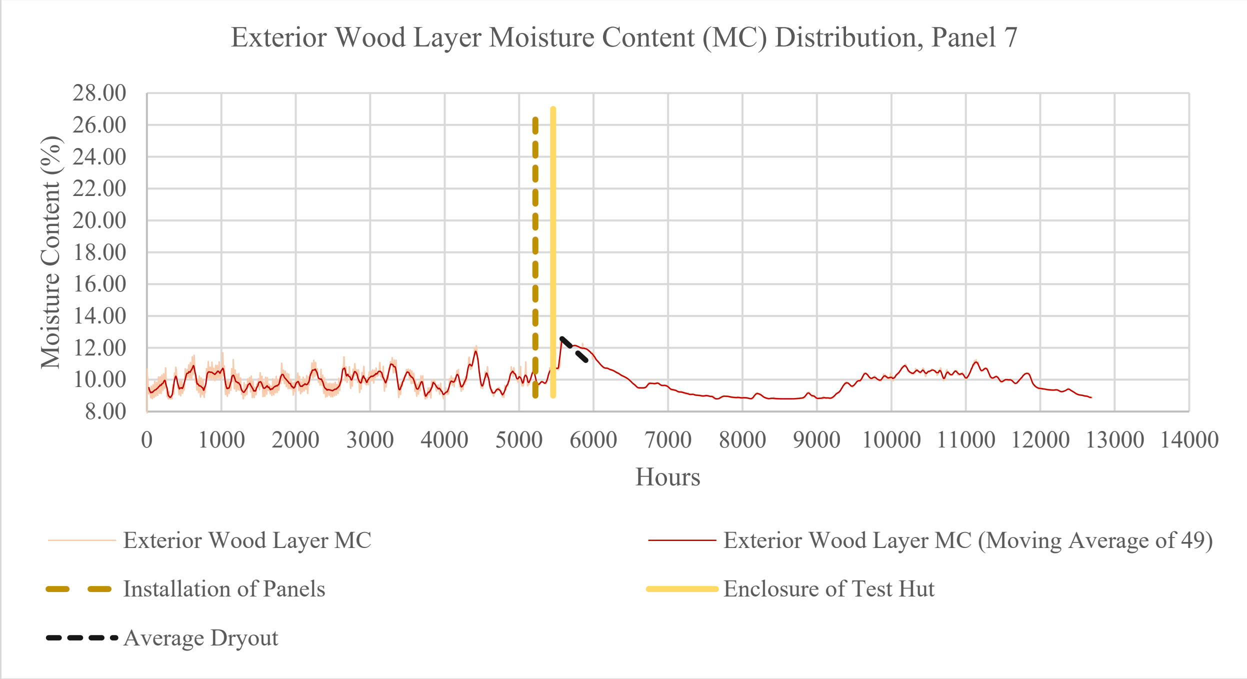

Figure 38: Exterior Wood Layer Moisture Content (MC) Distribution, Panel 7

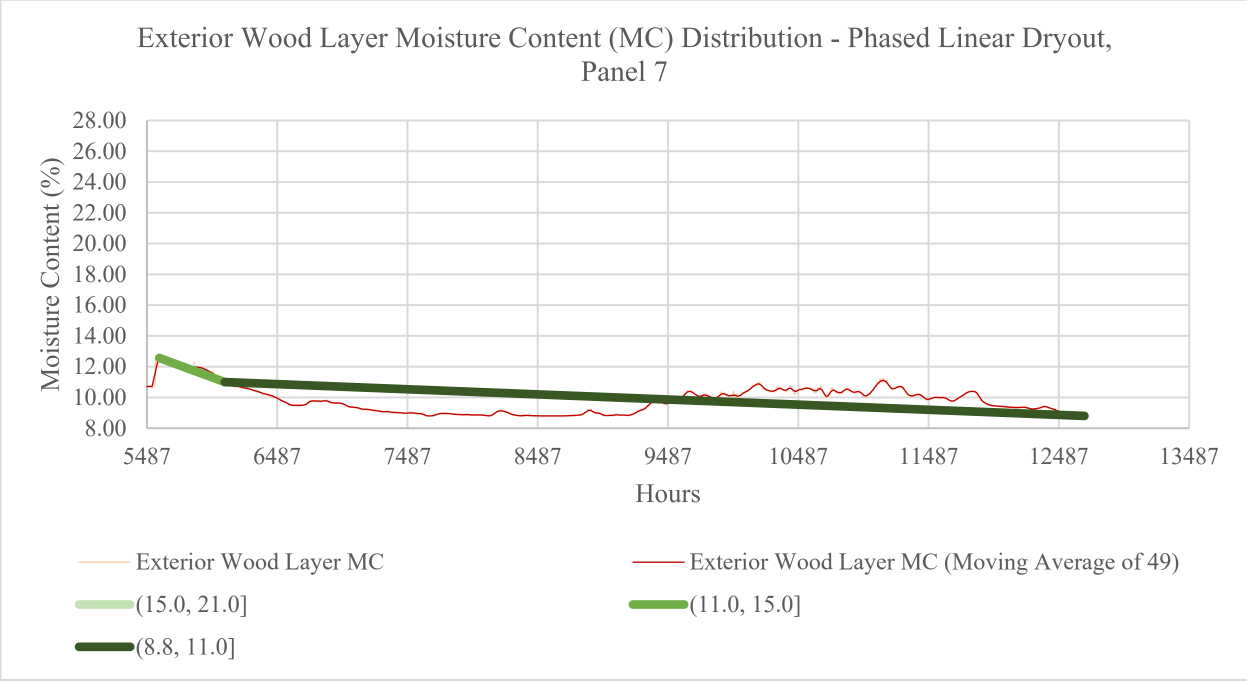

Figure 39: Exterior Wood Layer Moisture Content (MC) Distribution - Phased Linear Dryout, Panel 7

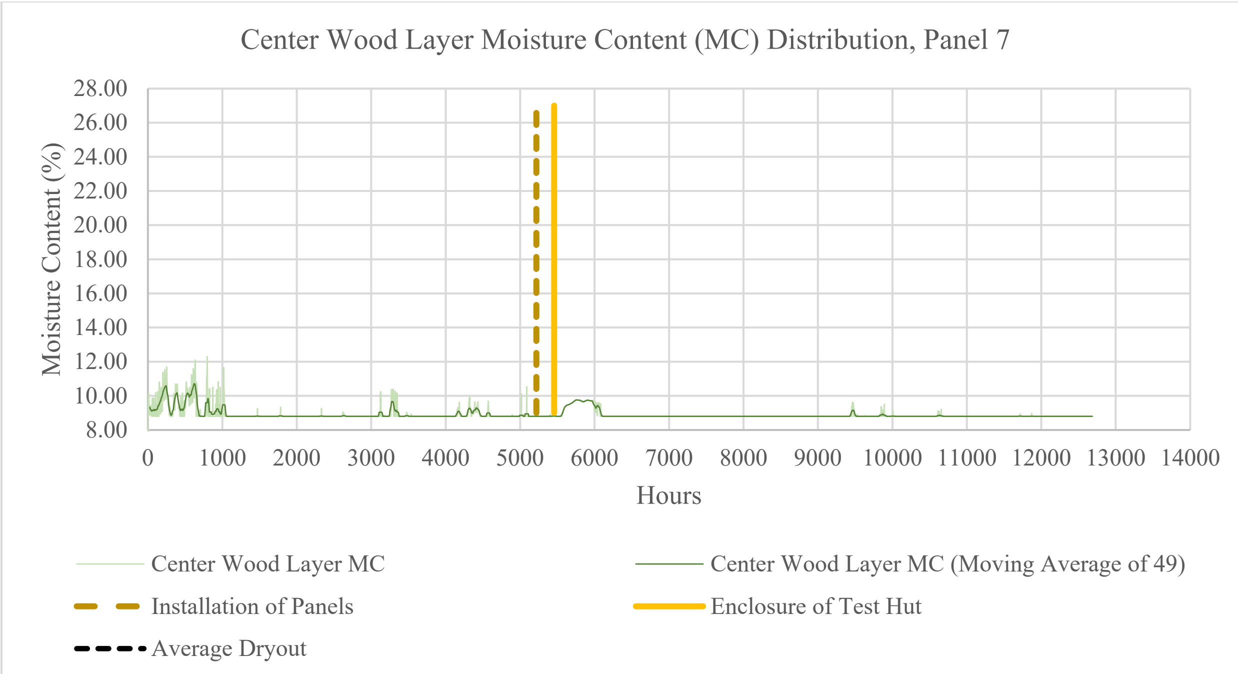

Figure 40: Center Wood Layer Moisture Content (MC) Distribution, Panel 7

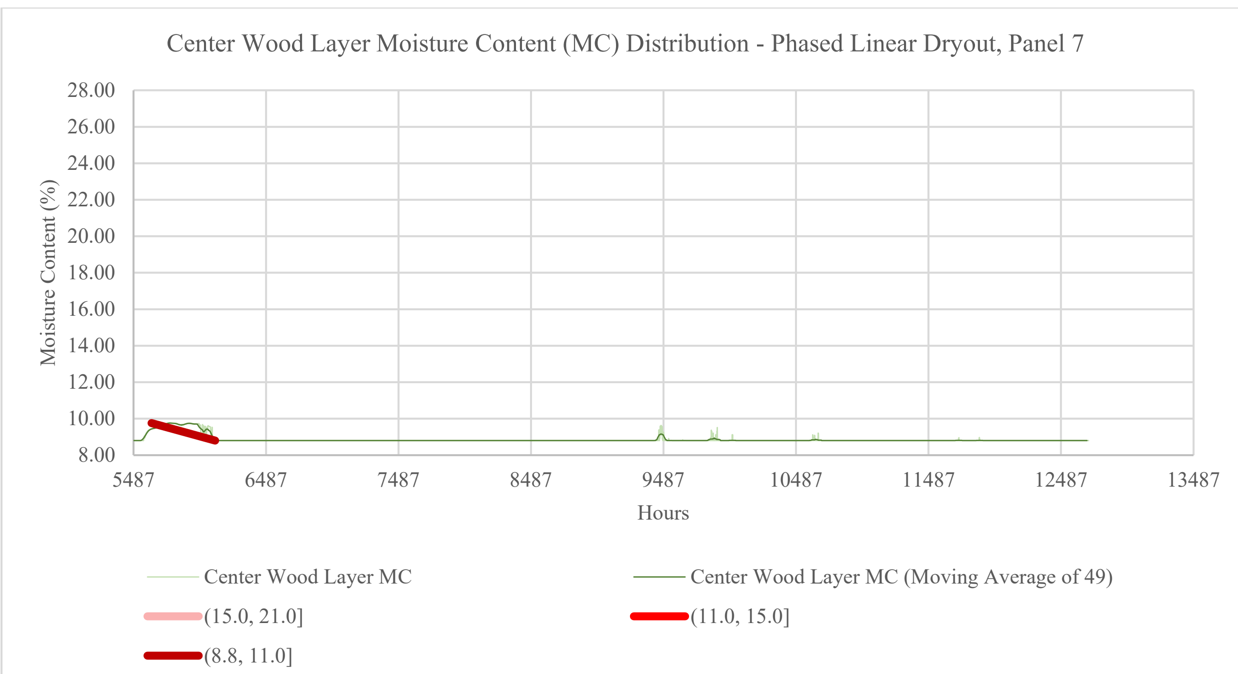

Figure 41: Center Wood Layer Moisture Content (MC) Distribution - Phased Linear Dryout, Panel 7

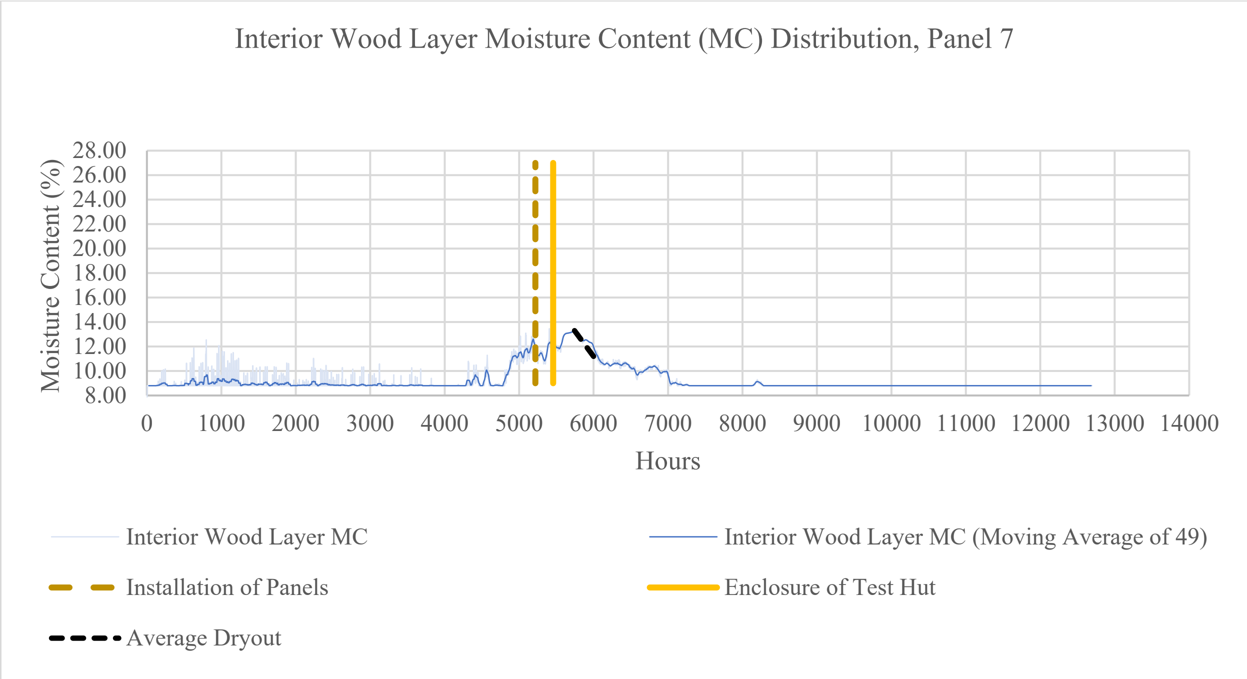

Figure 42: Interior Wood Layer Moisture Content (MC) Distribution, Panel 7

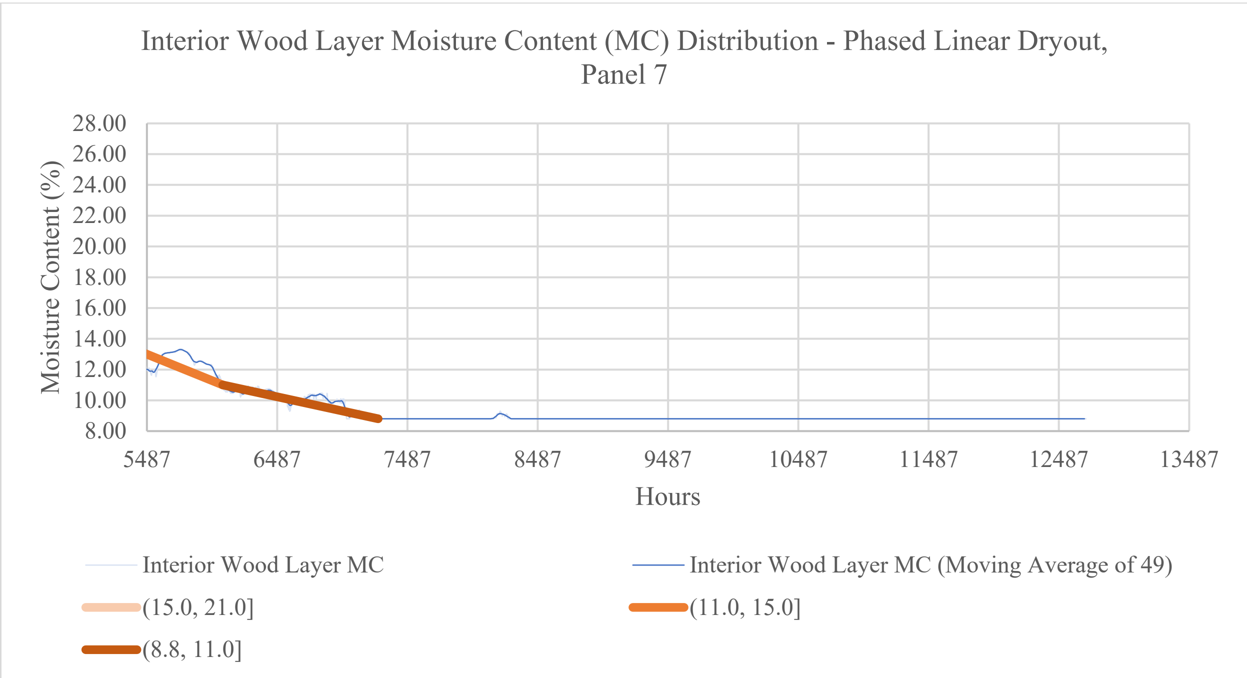

Figure 43: Interior Wood Layer Moisture Content (MC) Distribution - Phased Linear Dryout, Panel 7

APPENDIX F: Panel 8 Moisture Content Distributions

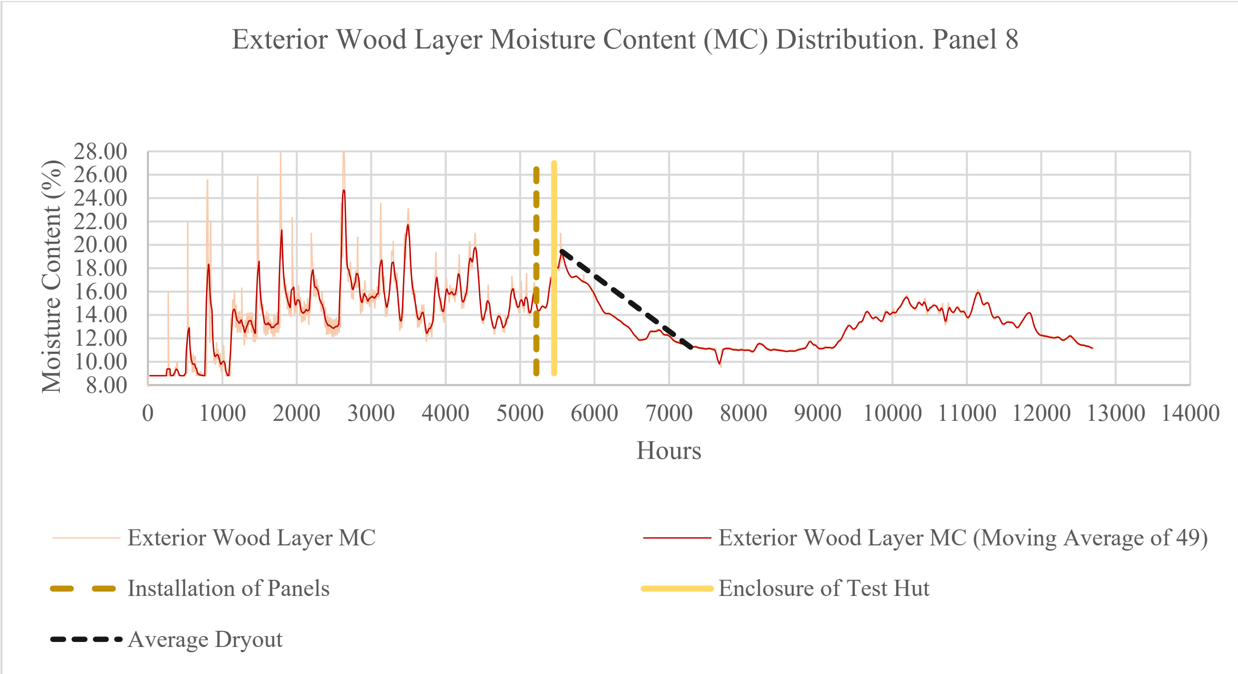

Figure 44: Exterior Wood Layer Moisture Content (MC) Distribution, Panel 8

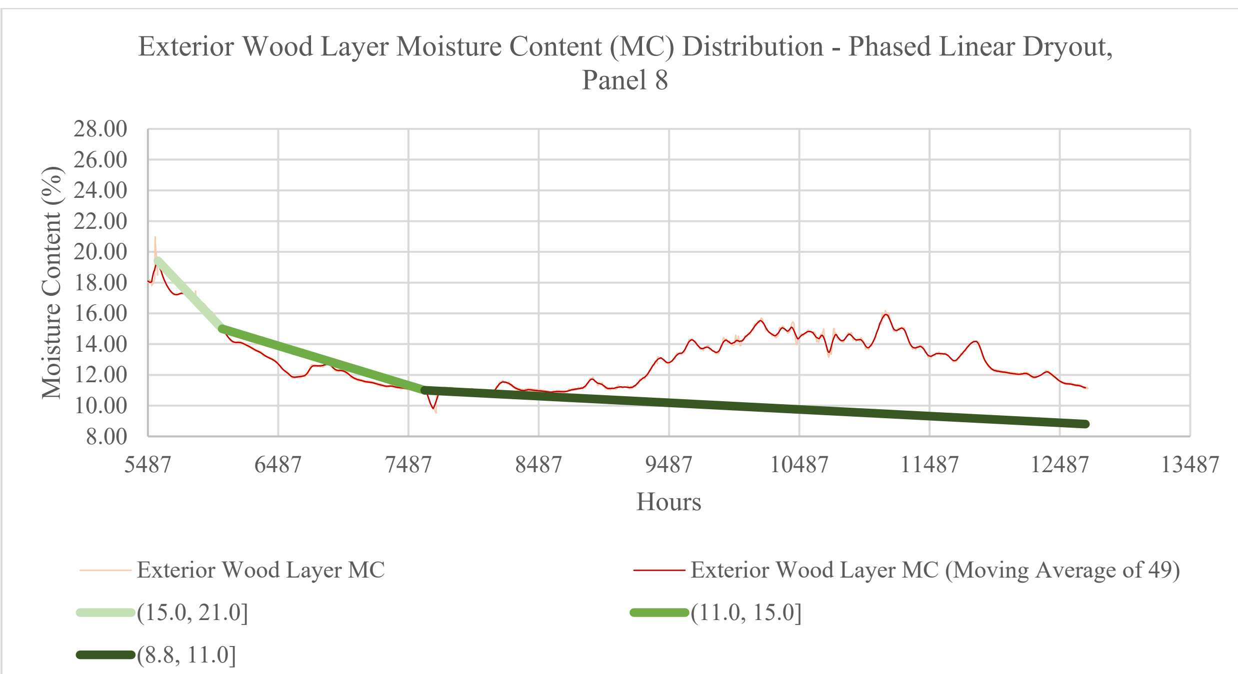

Figure 45: Exterior Wood Layer Moisture Content (MC) Distribution - Phased Linear Dryout, Panel 8

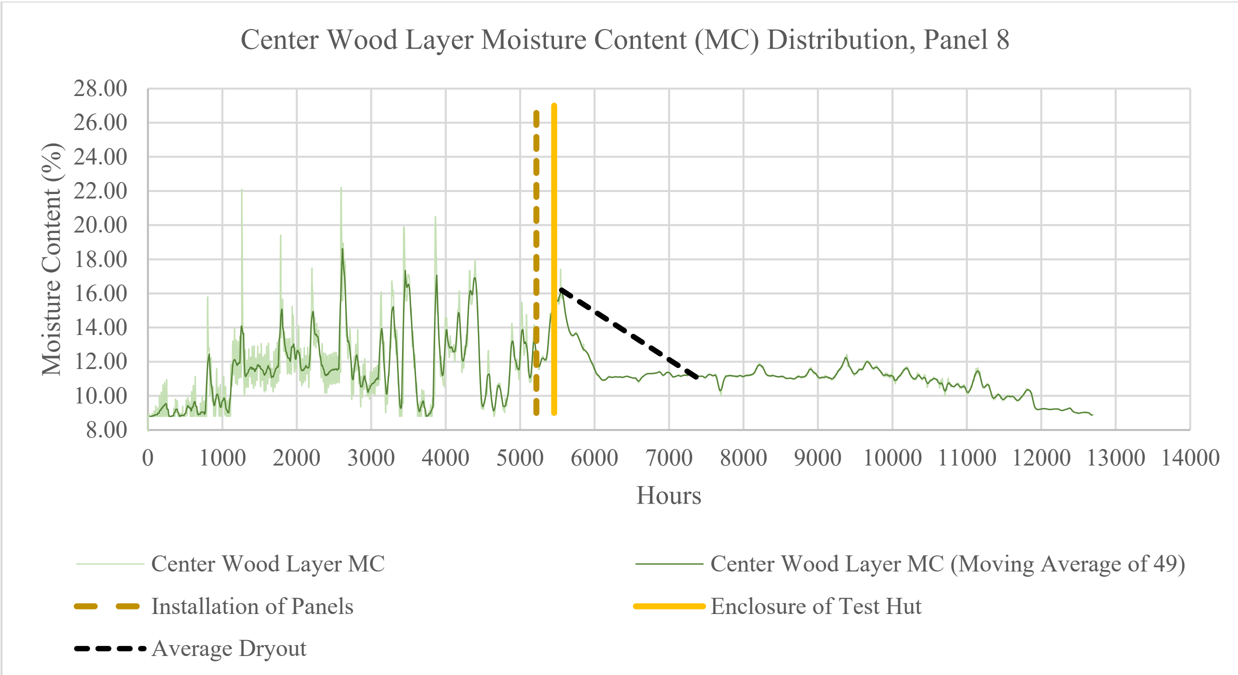

Figure 46: Center Wood Layer Moisture Content (MC) Distribution, Panel 8

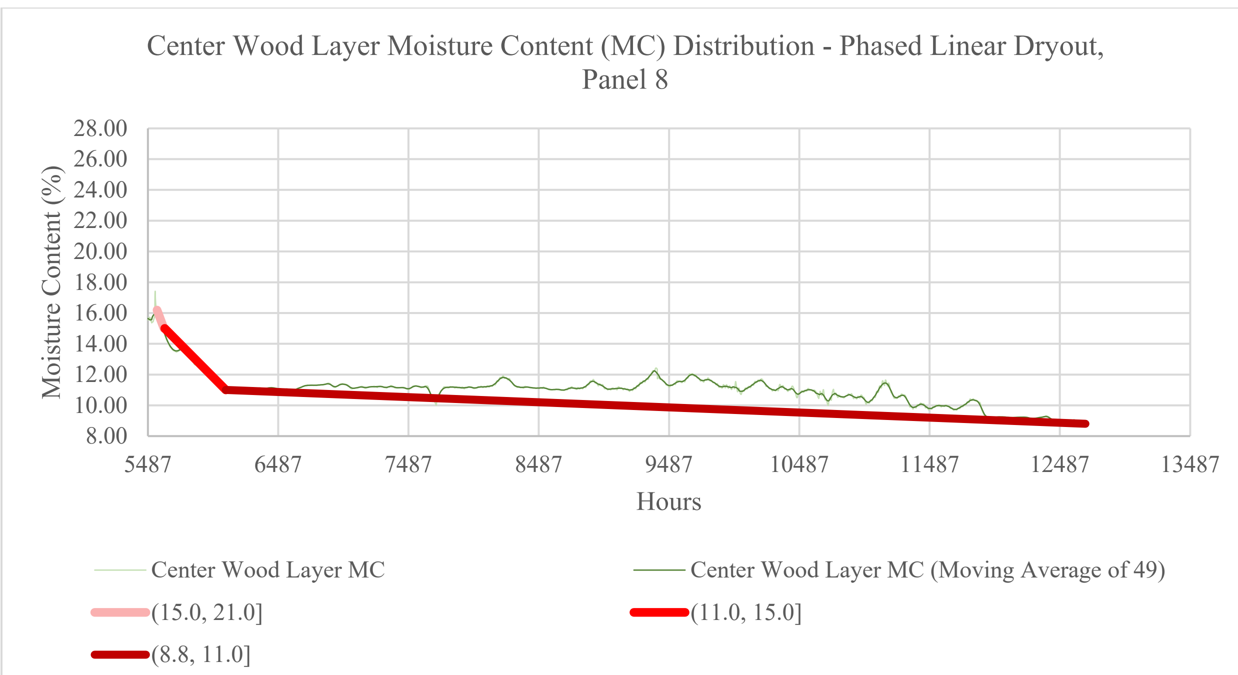

Figure 47: Center Wood Layer Moisture Content (MC) Distribution - Phased Linear Dryout, Panel 8

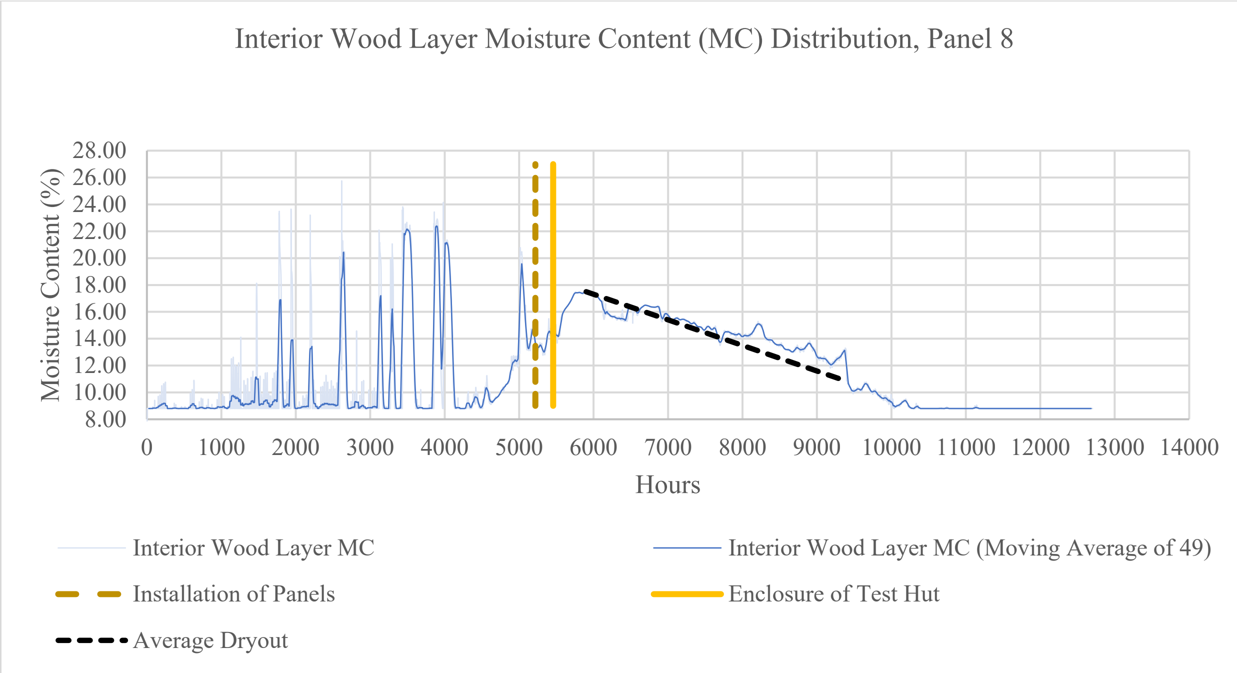

Figure 48: Interior Wood Layer Moisture Content (MC) Distribution, Panel 8

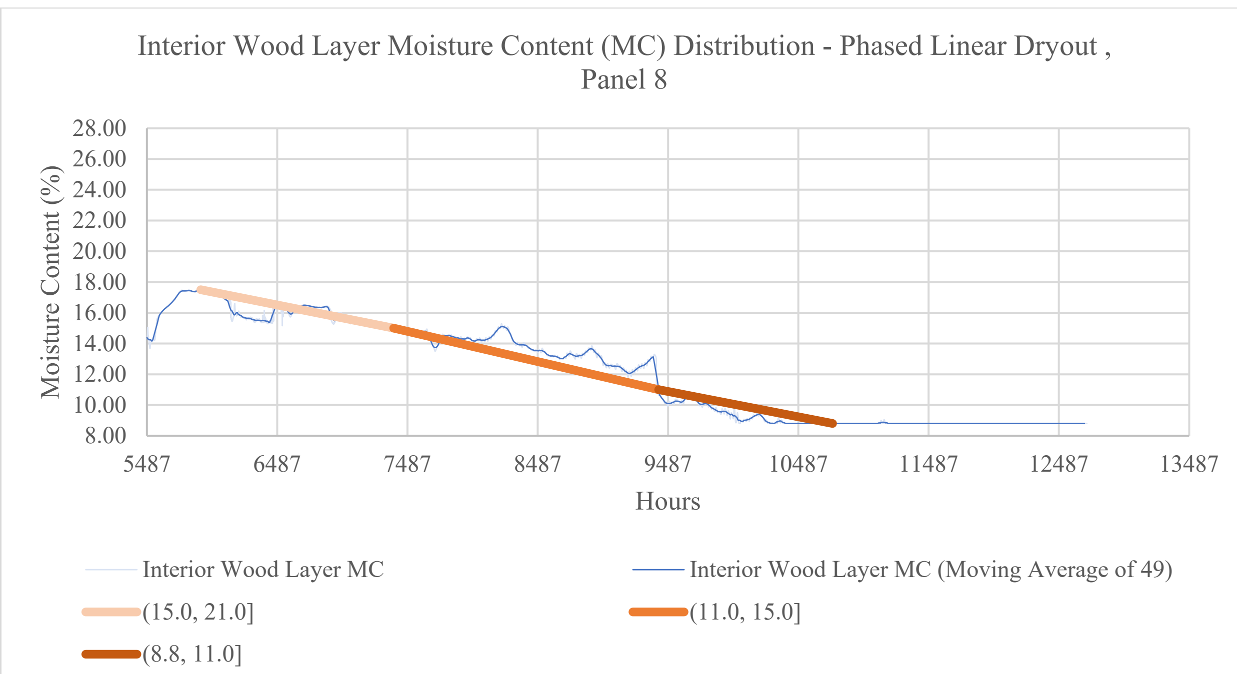

Figure 49: Interior Wood Layer Moisture Content (MC) Distribution - Phased Linear Dryout, Panel 8

APPENDIX F: Peak Moisture Content versus High Dryout Phase, by Layer

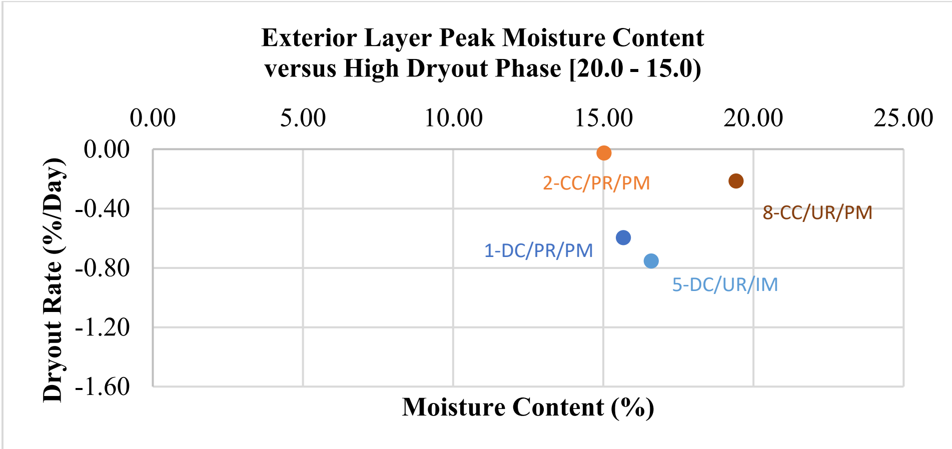

Figure 50: Exterior Layer Peak Moisture Content versus High Dryout Phase [20.0 - 15.0)

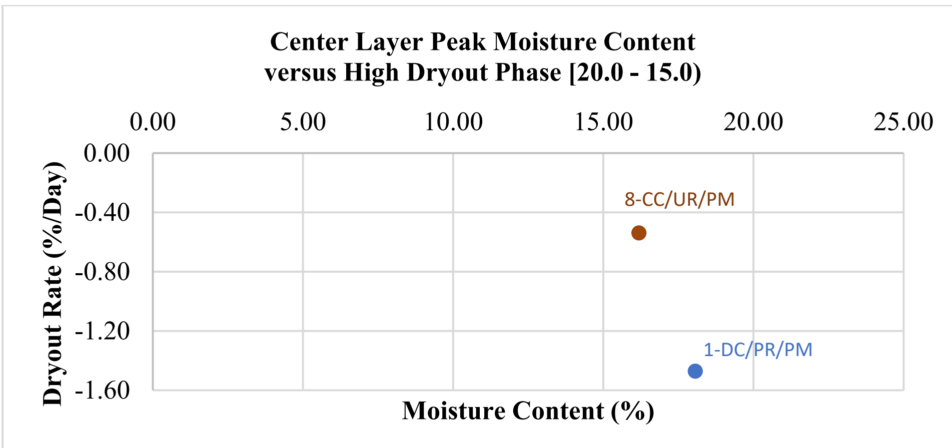

Figure 51: Center Layer Peak Moisture Content versus High Dryout Phase [20.0 - 15.0)

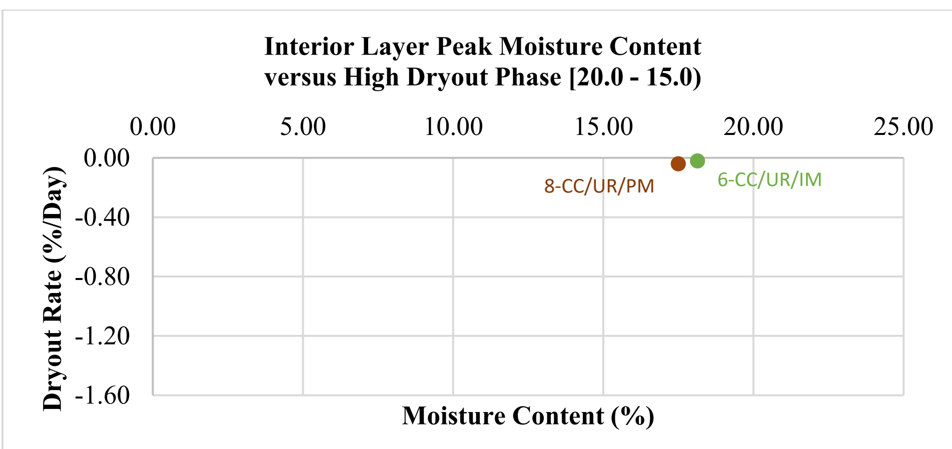

Figure 52: Interior Layer Peak Moisture Content versus High Dryout Phase [20.0 - 15.0)

APPENDIX G: Peak Moisture Content versus Intermediate Dryout Phase, by Layer

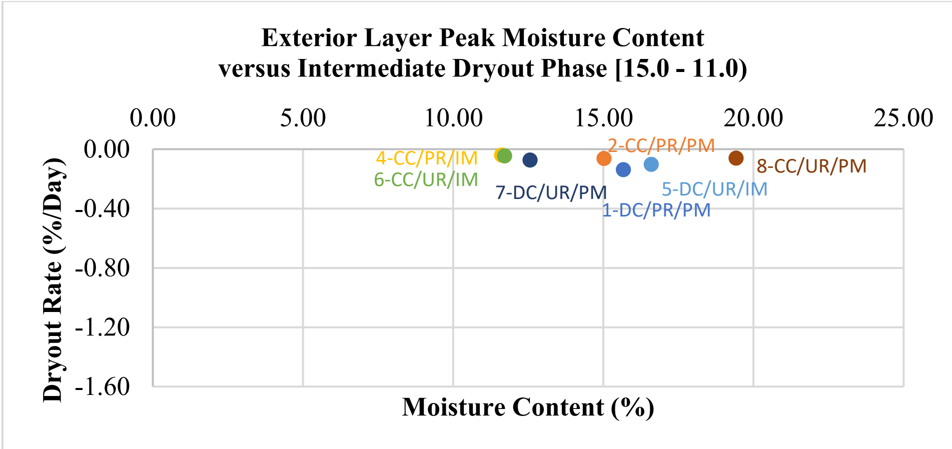

Figure 53: Exterior Layer Peak Moisture Content versus Intermediate Dryout Phase [15.0 - 11.0)

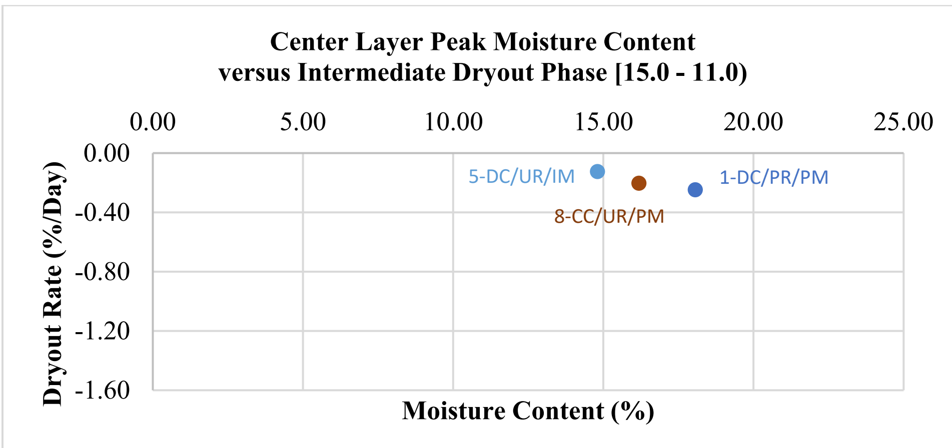

Figure 54: Center Layer Peak Moisture Content versus Intermediate Dryout Phase [15.0 - 11.0)

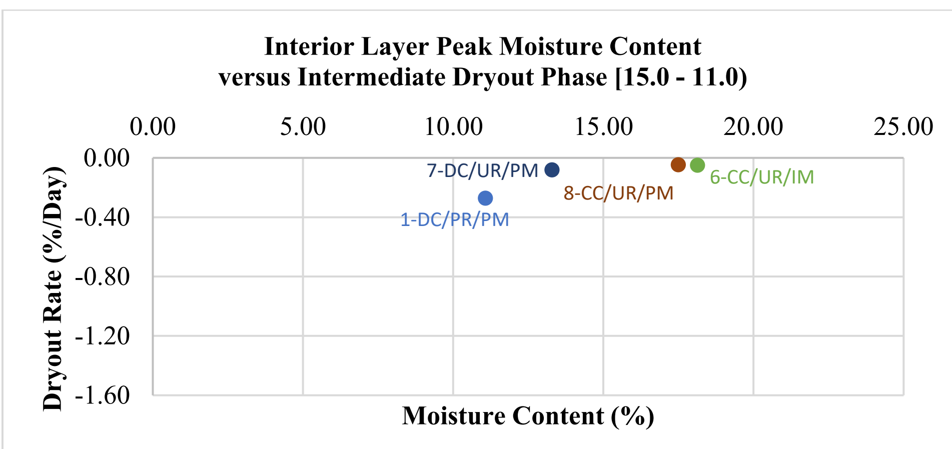

Figure 55: Interior Layer Peak Moisture Content versus Intermediate Dryout Phase [15.0 - 11.0)

APPENDIX H: Peak Moisture Content versus Low Dryout Phase, by Layer

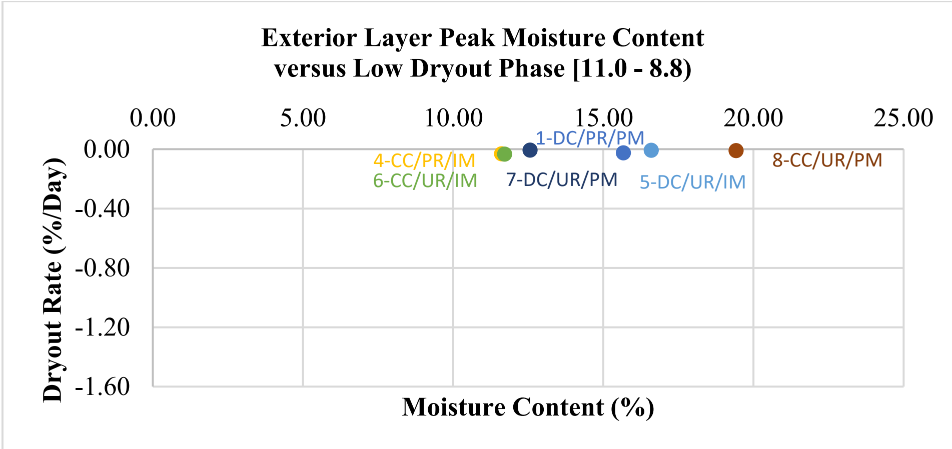

Figure 56: Exterior Layer Peak Moisture Content versus Low Dryout Phase [11.0 - 8.8)

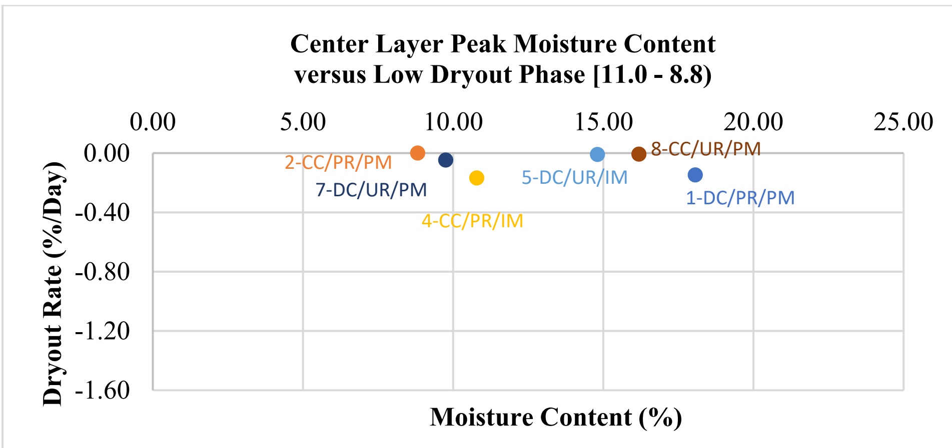

Figure 57: Center Layer Peak Moisture Content versus Low Dryout Phase [11.0 - 8.8)

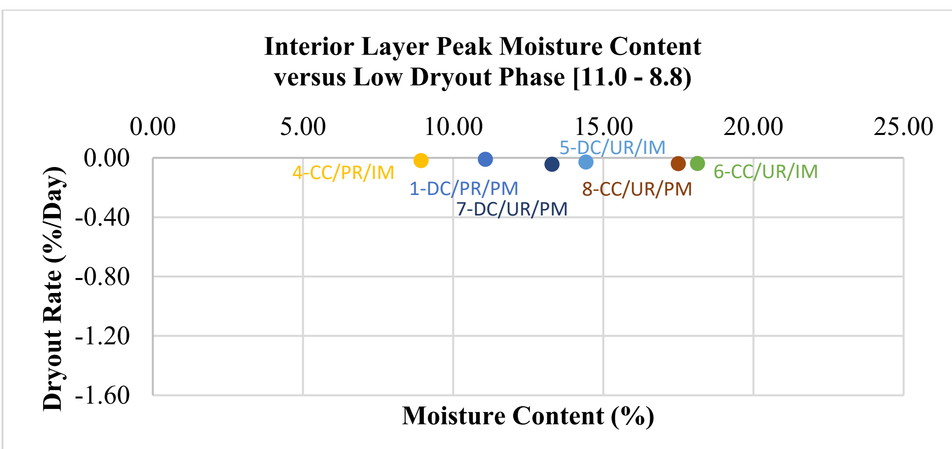

Figure 58: Interior Layer Peak Moisture Content versus Low Dryout Phase [11.0 - 8.8)