MOISTURE UPTAKE TESTING FOR CLT FLOOR PANELS IN A TALL WOOD BUILDING IN VANCOUVER

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ABSTRACT

Cross laminated timber (CLT) and mass timber construction is a promising structural technology that harnesses the advantageous structural properties of wood combined with renewability and carbon sequestering capacities not readily found in other major structural materials. However, as an organic material, mass timber is susceptible to biodeterioration, and when considered in conjunction with increased use of engineered wood materials, particularly in more extreme environments and exposures, it requires careful assessments to ensure long-term performance.

A promising approach towards reducing construction moisture in CLT and other mass timber assemblies is to protect the surfaces with a water-resistant coating. To assess this approach, a calibrated hygrothermal model was developed with small and large scale CLT samples, instrumented with moisture content sensors at different depths, and treated with different types of water resistant coatings exposed to the Vancouver climate. The models were further validated with additional moisture content sensors installed in a mock-up floor structure of an actual CLT building under construction. Biodeterioration studies assessing fungal colonization were undertaken using the modified VTT growth method and a Dose-Response model for decay potential.

The research indicates that CLT and mass timber is susceptible to dangerously high moisture contents, particularly when exposed to liquid water in horizontal applications. However, a non-porous, vapour impermeable coating, when applied on dry CLT, appears to significantly reduce the moisture load and effectively eliminate the risk of biodeterioration. This work strongly suggests that future use of CLT consider applications of a protective water-resistant coating at the manufacturing plant to resist construction moisture. The fungal study also highlights the need for a limit state design for biodeterioration to countenance variance between predicted and observed conditions.

Introduction

Cross laminated timber (CLT) and mass timber construction is a promising structural technology that harnesses the advantageous structural properties of wood combined with renewability and carbon sequestering capacities not readily found in other major structural materials. However, as an organic material, CLT is susceptible to biodeterioration. At moisture contents (MC) greater than 20% MC, CLT is susceptible to surface fungal attack by moulds. At moisture contents greater than 25% MC (near the fiber saturation point), the CLT is at risk of structural damage by decay and rotting fungi (Zabel and Morrell 1992).

Construction moisture, either from precipitation or the installation of a cement-based screed, can be stored by the floor assembly due to the significant storage capacity and the physical characteristics of CLT. Liquid water under hydraulic head can seep between the cracks and joints in the outer plies of the CLT thereby penetrating deep into the core. With the thicknesses of wood under consideration and its resistance to vapour diffusion impermeable, it can take years for this moisture to fully diffuse through the thickness of the panels. The CLT may then become at risk if the safe storage threshold is surpassed. Preliminary research by Lepage (2012) and McClung (2013) suggest that CLT could be at risk of premature biodeterioration if subjected to large moisture loads.

Due to the importance of CLT as a primary structural material, evaluation of the risks of construction moisture are required. This study compares full scale mock-ups of the as-constructed building sections with calibrated hygrothermal models based on small and medium scale assemblies. The models are then used to evaluate different protective measures of water resisting coatings with respect to changing construction moisture loads. To assess the associate risks, an empirical mould growth index and a dose-response decay risk model are used to evaluate the service and ultimate state risks, respectively.

Approach

In support of the planning and design of a tall wood building project, referred to herein as the Tall Wood Residence (TWR), several phases of field exposure testing and monitoring were completed to research and assess (1) the effects of exposure to rain and (2) application of a cementitious floor topping on the wood moisture content of the cross-laminated timber (CLT) floor panels, two common situations found in larger commercial. This consisted of the following three phases

1) Phase 1– Sample Testing
    - To evaluate (1) rain exposure, small 400x400mm sections of CLT were instrumented with moisture content sensors to evaluate the effects of water resistant coatings
    - To evaluate (2), moisture loads from cementitious floor topping, a mock-up of the TWR floor assembly was constructed and instrumented with moisture content sensors. Eight different coating types were applied to the mock-up wood structure.
2) Phase 2 – Hygrothermal Calibration
    - The results of the Phase 1 monitoring were used to calibrate hygrothermal computer models of the same floor assemblies. Predictive modelling assessed the longer-term effects of the various wetting and drying patterns.
3) Phase 3 – Fungal Contamination Model
    - The calibrated hygrothermal model will be used to infer the risks of fungal contamination, for both surface moulds and decay, using the VTT *Improved Model to Predict Mold Growth in Building Materials* (Viitanen and Ojanen 2007) for surface mould contamination, and Dose-Response Relationship for Fungal Decay (Brischke and Rapp 2008), for structural decay, respectively. Detailed descriptions of these deterioration models are beyond the scope of this paper and are thus only discussed cursorily.

The TWR was also instrumented with moisture content sensors. However, insufficient data were available at the time of this research to evaluate the long-term predictions of the hygrothermal simulations. On overview of the data collected and findings to date see the CCBST paper *Vertical Movement and Moisture Performance Monitoring of Pre-Fabricated Cross Laminated Timber – Featured Case Study: UBC Tallwood House* (Mustapha et al, 2017).

EXPERIMENTAL SET-UP

To evaluate the effects of construction moisture on CLT, two experiments were devised: (1) a series of 6 CLT floor sections with different coatings to evaluate exposure to precipitation, and (2) a partial floor assembly of the TWR with eight different coatings, which includes a screed topping, to evaluate the moisture load effects of a cementitious floor topping. The screed topping was formed using plywood around the perimeter of the floor mock-up.

Moisture content sensors were installed into various layers of the CLT test sample at each of the test areas, and various wood coatings were applied as required by the experimental protocol. The moisture sensors are made from long threaded stainless steel pins with an insulating plastic sheathing for the entire length except at the tip where the metal contact is used to measure the wood moisture content. The pins were installed from the underside of the CLT panel at the locations as shown below in Figure 1 for each of the test areas. The "edge" sensors were situated within 12.7mm of the edge, and the "center" sensors were a minimum of 300mm from the edge. Measurements were taken on an hourly basis. As these samples were left in an outdoor environment, it was assumed that thermal equilibrium would be achieved and thus no temperature sensors were inserted within the CLT samples.

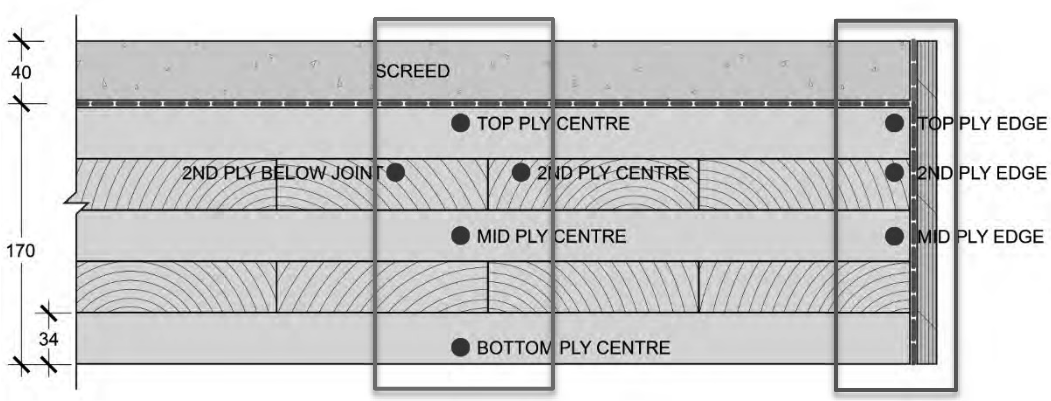


Figure 1 Conceptual MC pin location of CLT test sample showing sensor locations, all dimensions in millimeters. The depth of the MC pins are approximate. The green dashed line indicates the coating treatment. Sensors outlined in the red square represent 'center' readings of the sample, whereas sensors outlined in blue represent 'edge' readings.

A total of nine types of coatings were considered, using the coatings listed in Table 1.

Table 1: List of All Coatings Used in the Two Phases of CLT Sample Testing (with short form bolded for data identification)

Wood **preservative**	**Polyurethane** primer
Silicone wood coating	**Porous** substrate primer
Urethane resin wood sealer	**No coating** (baseline)
Impermeable self-adhered membrane (**SAM**)	No coating / **no screed** topping (Baseline)

Acrylic latex primer	

Exposure to Precipitation

Six CLT samples were exposed to the environment with moisture pins installed into each sample to monitor the wetting of the top ply at the center of panel and at the edge to capture end grain effects (see Figure 2). The samples were coated on all six sides in accordance with the manufacturer's instructions. The samples were left exposed for approximately 20 weeks, from January 20th to June 7th, 2016.

Figure 2: Exposed CLT samples

Exposure to Cementitious Topping

A CLT floor plate, dimensions of 1220mmx171mmx5m, was constructed and installed in the TWR mock-up on the first-floor level. The floor mock-up was sheltered from precipitation. The intention of the monitoring was to measure the performance characteristics of the wood layers in the CLT sample when exposed to a cementitious screed topping, comparing various protective coatings at the top surface of the wood. The different coatings were applied to the top and sides of the same CLT plate, then a cementitious screed topping was installed at the top of the test sample to a thickness of 40mm. The mock-up was monitored between December 2015 and February 2016.

Figure 3: CLT test sample partial screed topping removal and wetting test

RESULTS

Both the rain exposure phase and cementitious topping phases were exposed to ambient environmental conditions, with the former having direct exposure to precipitation, whereas the latter was in a covered environment. A local (within 7km) meteorological station was used to collect air temperature, relative humidity, and hourly rainfall amounts. These data were used to calibrate the hygrothermal models, which then permitted a predictive comparison using typical meteorological year weather data.

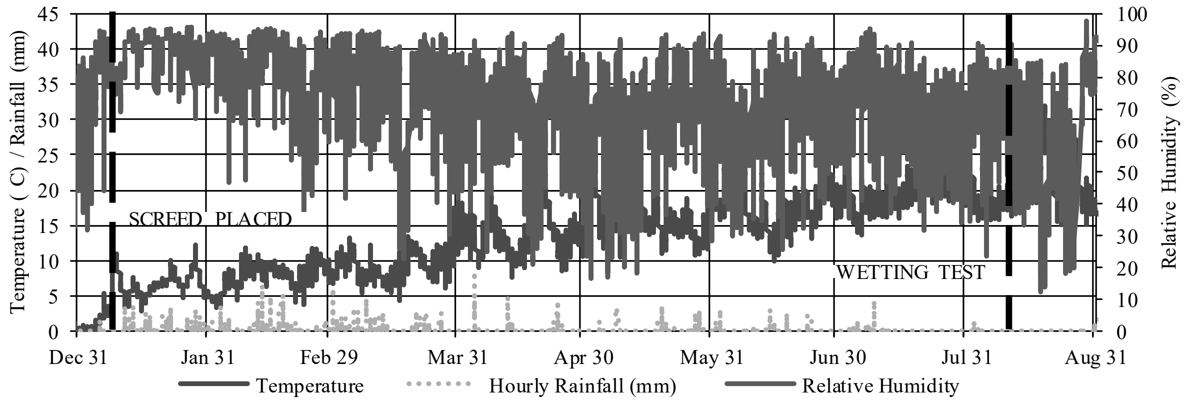


Figure 4: Outdoor temperature, relative humidity, and hourly rainfall weather data in Vancouver, BC, over the duration of the monitoring period.

Exposure to Rain

The results of the monitoring of the exposed CLT samples show the characteristics of each coating when exposed to direct moisture mainly in the form of rain and night-sky induced condensation. Sensors were left in place for a total of approximately 20 weeks over the winter-spring season. Figure 5 and Figure 6 show the results of the full monitoring period at the top ply of the exposed samples and the outside edge of three of the samples. Three coating types were considered to demonstrate the range of moisture contents observed. An on-site meteorological tower was used to measure ambient conditions, including hourly rainfall.

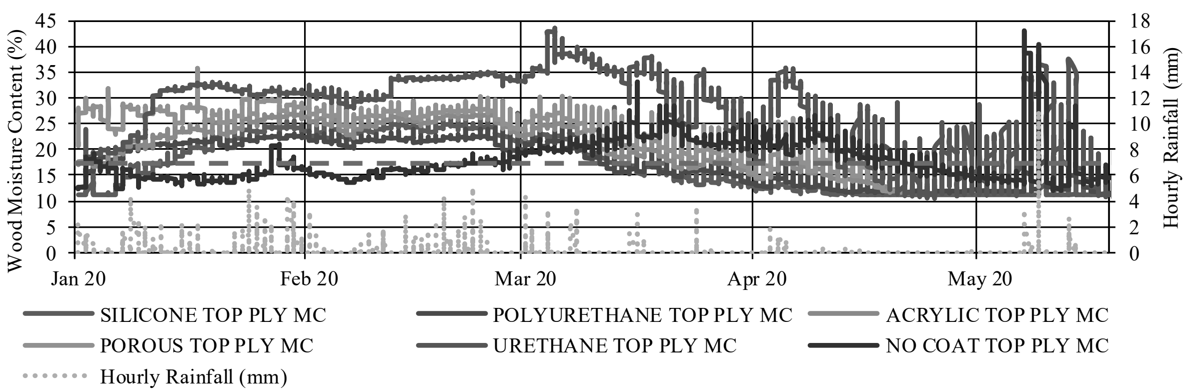


Figure 5: CLT wood moisture content of the top ply for each exposed test sample and the rainfall during the monitoring period

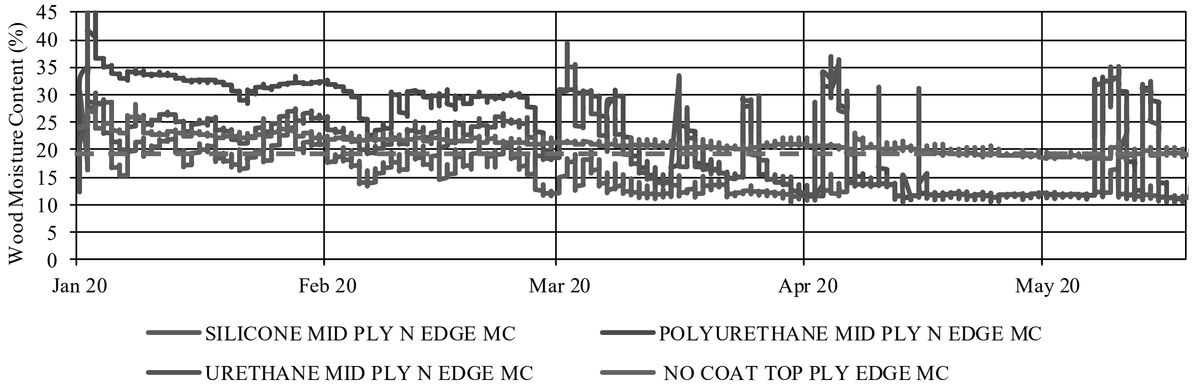


Figure 6: CLT wood moisture content of the middle ply at the outside edge for the Polyurethane, Urethane, and Silicone exposed samples during the monitoring period

This monitoring shows the wetting of all CLT samples above the 20% MC threshold due to the frequent rain events during the winter period, with the urethane resin coating showing the most wetting to over 40% MC at the top ply. Over the spring period, all samples appear to dry down below 20% MC at the top ply and outside edge. The No Coat center and edge sensors do not appear to experience significant variations, despite precipitations. It is possible that these pins may have poor contact with the wood or that they are installed in a layer of heartwood within the same wood laminate.

Exposure to Cementitious Topping

The measured data is presented in the summary graph in Figure 7, showing a comparison of each of the coatings, and how the wood moisture content at the top CLT ply behaves at all test areas. For clarity, only the CENTRE measured location in the top ply is shown for each test area (see Figure 1). These sensors are placed closest to the screed topping just beneath the top surface of the CLT panel and thus measure more readily the initial wetting from the screed topping compared to the other moisture pins placed in the panel. These measured locations are considered a better indicator of the coating/membrane performance for this analysis. The plot also contains time markers for when the coatings were applied and when the screed topping was placed. Also included for reference is a horizontal marker line at 20% moisture content to indicate the cautionary level of moisture that could lead to fungal growth in the wood.

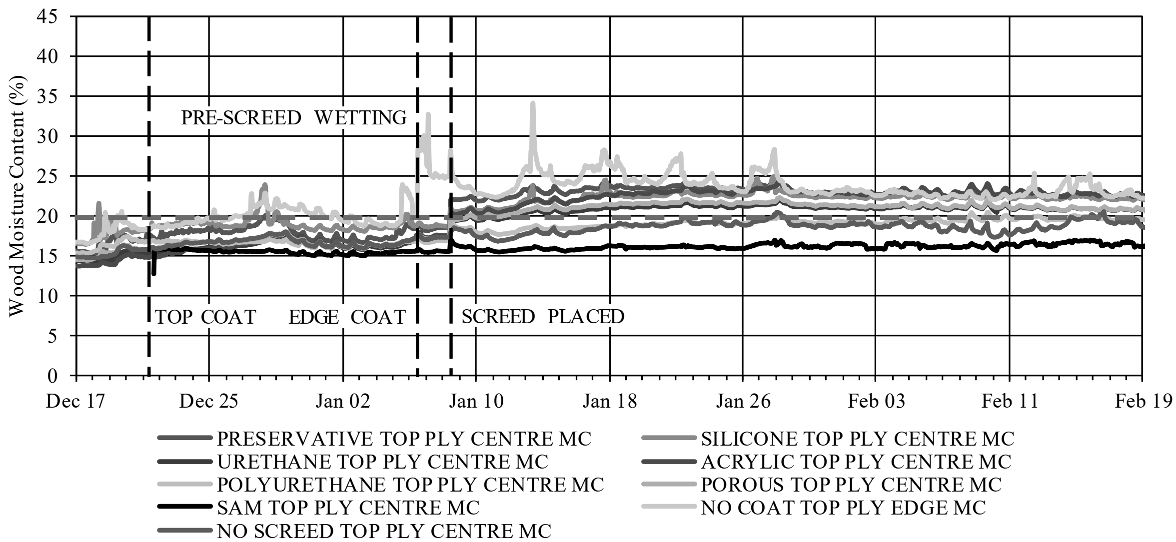


Figure 7: CLT wood moisture content beneath all test areas

It is important to note that the "No Coat" sample in the testing here was accidentally exposed to moisture before the screed topping was place, and is therefore excluded from this analysis. As a substitute for this data set, the preservative treated sample is considered to have a coating with minimal impact on wetting. The Top Ply Edge sensor was malfunctioning and could not be used.

The following graphs show the long-term moisture content readings at the CLT test sample. The graphs include a time marker for the screed placement and a wetting test completed at the end of the monitoring period. Figure 8 shows the results at the top ply over the full monitoring period.

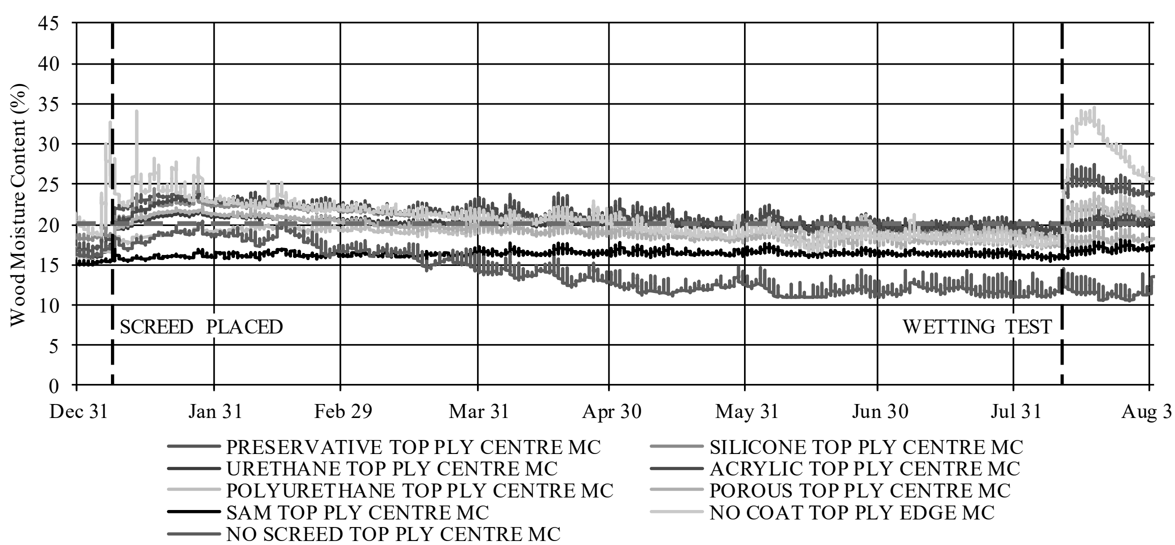


Figure 8: Long term CLT wood moisture content beneath all test areas (note the Top Ply Edge sensor location shown was exposed to moisture prior to screed placement, and no data was collected from the Top Ply Centre location due to a damaged sensor)

HYGROTHERMAL ANALYSIS

To extrapolate the measured data for different conditions, a hygrothermal model was prepared. The models were calibrated to the results of the small scale CLT samples. Three different alternatives were modelled, based on the performance of three classes of coatings. The material properties of these artificial coatings are provided in Appendix A.

1. Vapour permeable hydrophobic sealer (i.e. silicone),
2. Low-permeable hydrophilic sealer (i.e. urethane)
3. Impermeable, waterproof membrane (i.e. self-adhered membrane, SAM).

Hygrothermal analysis was undertaken to ascertain the efficacy of the different sealers when exposed to different conditions. By first calibrating the hygrothermal models to the empirical results obtained in Phase 1, different scenarios can be simulated to assess performance. The hygrothermal software selected was WUFI Pro® version 6.0.2.2027.DB.26.0.17.0 (Künzel, 1995), due to its ability to simulate vapour and liquid water flows in hygroscopic materials.

The WUFI model was developed with several ‘sense’ layers, taken at 6mm thickness, which corroborates to the approximate volume measured by electrical resistance moisture content pins (Figure 9). This enables comparisons between the simulation and measured results.

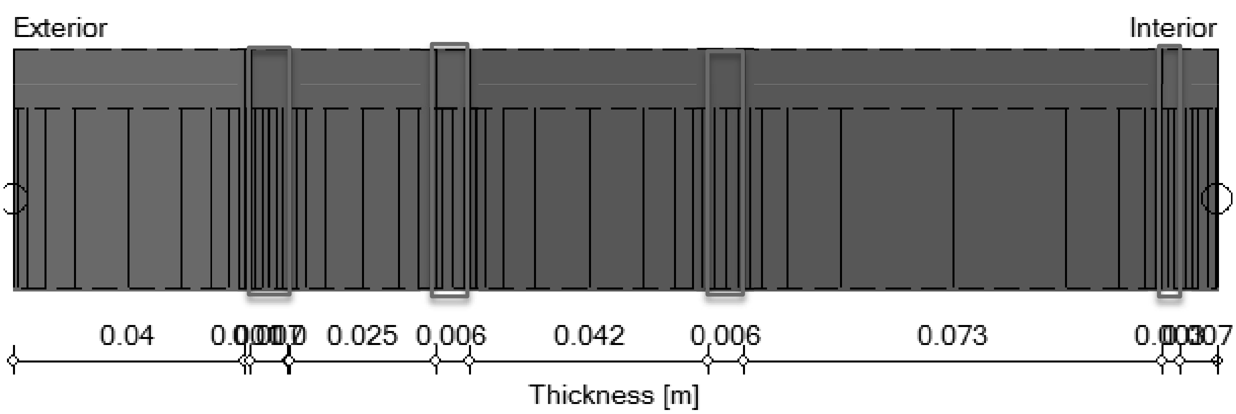


Figure 9: WUFI cross section showing 6mm thick sense layers, from left to right, Surface, Top Ply, Mid Ply, and Bottom Ply

Model Calibration

The models were calibrated by following a calibration sequence that incrementally adds complexity (i.e. new information or material properties) to previous models that found good agreement. The new layer material properties are modified within acceptable ranges within the published literature until a good match is obtained, within the error margin of the measurements (approximately 2%MC for species and temperature corrected moisture content pins). Material property data were collected on the manufacturer’s technical data sheets, and supplemented with literature for similar products and may be found in Appendix A. The baseline model consisted of calibrated CLT material property combined with a calibrated cementitious topping, shown in Figure 10.

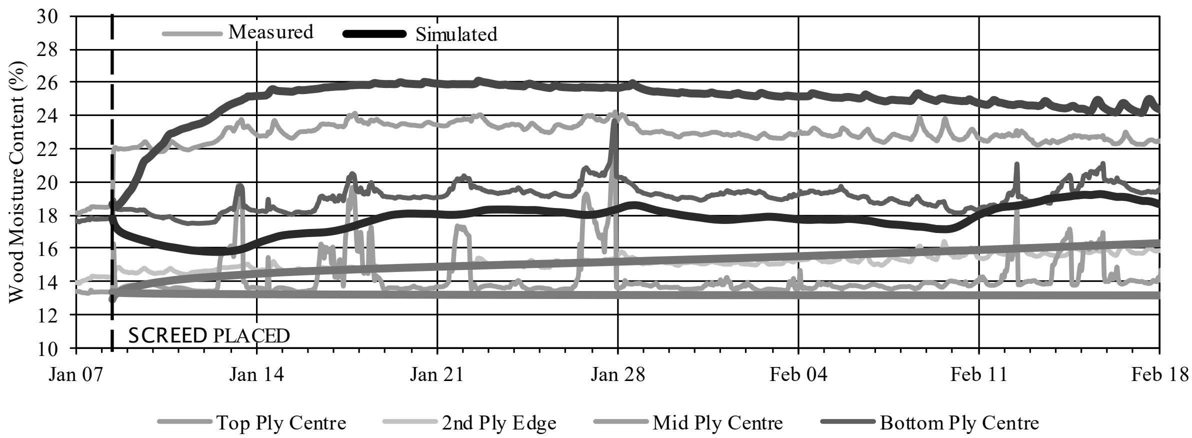


Figure 10: No-coat post-screed comparison between measured and simulated moisture contents

Modeling of the screed was achieved by first obtaining the moisture content profile of a CLT sample in the ambient environment. It was then imported as the initial moisture conditions, with the moisture content of the screed set to manufacturer's literature. In general, the moisture content trends between the measure and simulation were similar. Slight variances may be due to differences in the density of the material, but falls within the margin of error of the moisture content pins. Upon installation of the screed, the measured data jumps rapidly to 22% MC, which is not demonstrated by the simulation. This is likely due to the 1-dimensional nature of the software and hourly averaging function of the data logger system. Once the initial conditions settle, the trends are nonetheless comparable. Subsequently, calibration for the different water-resistant coatings was undertaken. The coatings were simulated by creating an artificial material layer, 1 mm thick, and calibrating the liquid diffusivity and vapour diffusion resistance factors (VDRF) to match the Phase 1 and Phase 2 experimental data. Material properties for these coatings may be found in Appendix A.

The polyurethane sealer layer was modified by providing a low vapour diffusion resistance factor (VDRF) in conjunction with a small liquid water uptake coefficient. With these modifications, good agreement was observed on the Top Ply sense layer (Figure 11). The spikes in the Bottom Ply layer are believed to be a result of shorting of the moisture content sensors; note that the peaks are roughly aligned with the simulated results and are aligned with expected values for the equilibrium moisture content.

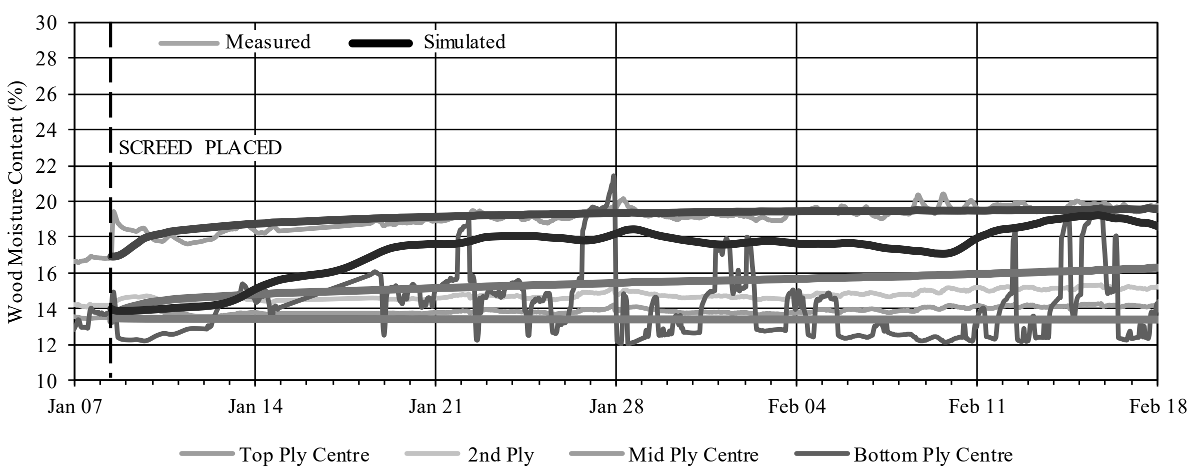


Figure 11: Polyurethane sealer post-screed comparison between measured and simulated moisture contents

The silicone sealer is known to be hydrophobic, but vapour permeable. Modification to the VDRF was undertaken until good agreement was observed with the measured data (Figure 12). Both the Top Ply and Bottom Ply respond closely to environmental conditions.

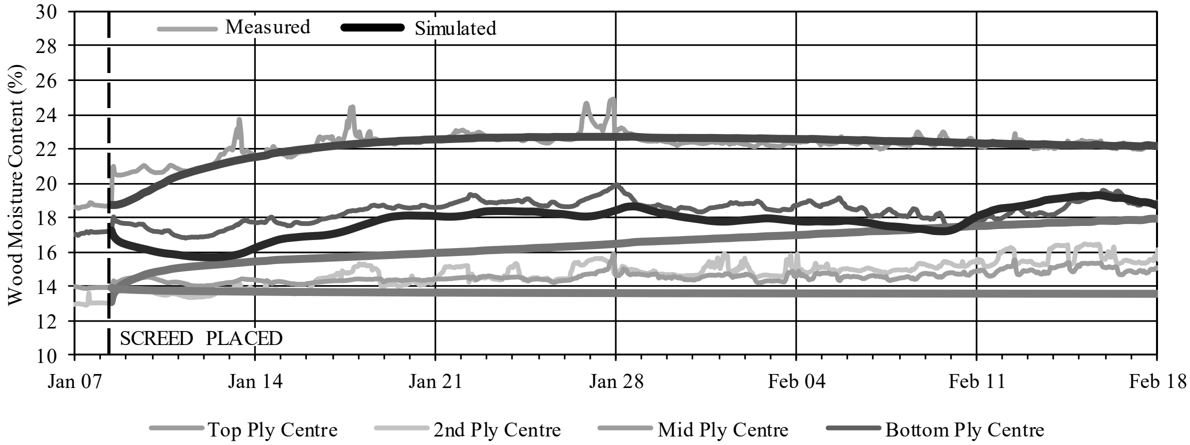
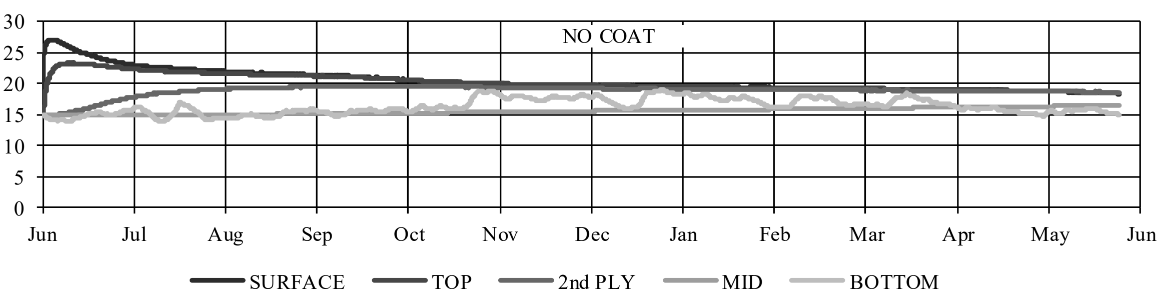


Figure 12: Silicone sealer post-screed comparison between measured and simulated moisture contents

Predictive Simulations

The baseline hygrothermal calibrations provided generally good agreement between the simulated models and the empirical models for CLT with a screed topping with no protective coating, an impermeable coating, and permeable sealer. This section will attempt to assess the performance under different initial starting conditions to quantify the best-case scenario with maximum drying capacity in the summer. The internal WUFI – Vancouver; cold-year was used for these simulations.

Assuming CLT panels with moisture contents below 15% and the installation of the cementitious screed on June 1st, the moisture content profiles in Figure 13 are predicted for uncoated CLT, CLT coated with polyurethane primer, and CLT coated with silicone sealer.



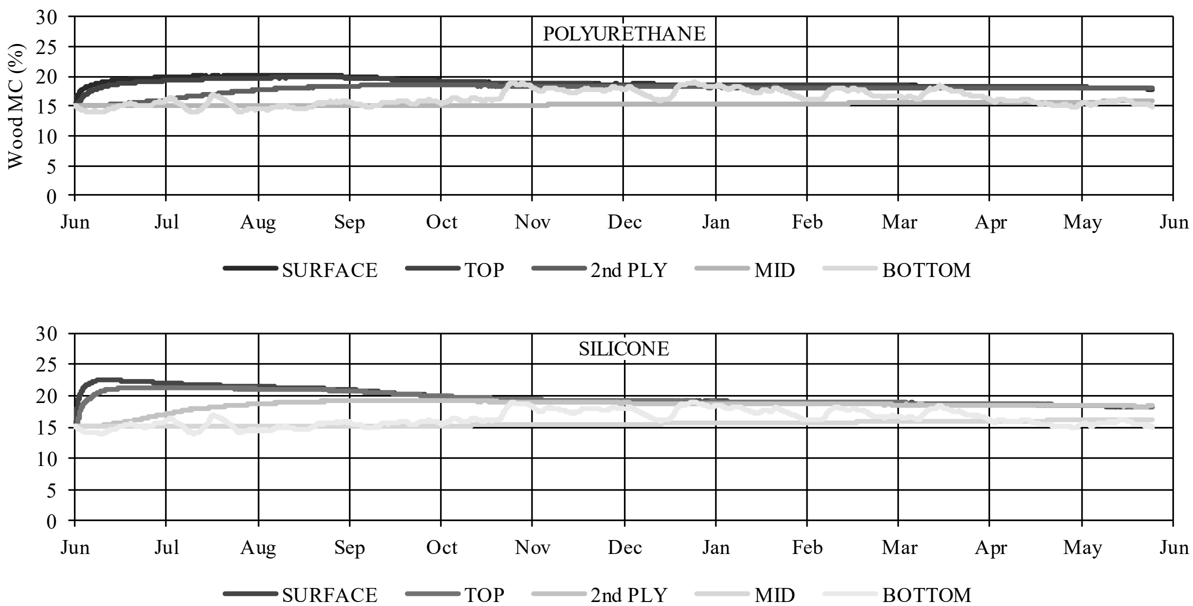


Figure 13: Predicted Performance – No Coating (Blue), Polyurethane coating (Red), and Silicone sealer (Green) at starting moisture content <15%.

Like the monitoring results, these simulations suggest that a coating will significantly reduce the wetting of the outermost layer of the CLT compared to the "No Coat" baseline, keeping it below the critical 26-28% moisture content required for decay. The only coating which appears to keep the CLT below the 20% threshold for mould is the polyurethane based sealer. It should be noted that any variation in the initial moisture content, installation quality, or variations in the screed can appreciably change the results of these simulations.

The ideal method to eliminate any impacts of construction moisture from the screed is to use an impermeable and waterproof coating, such as a self-adhered membrane, shown in Figure 14.

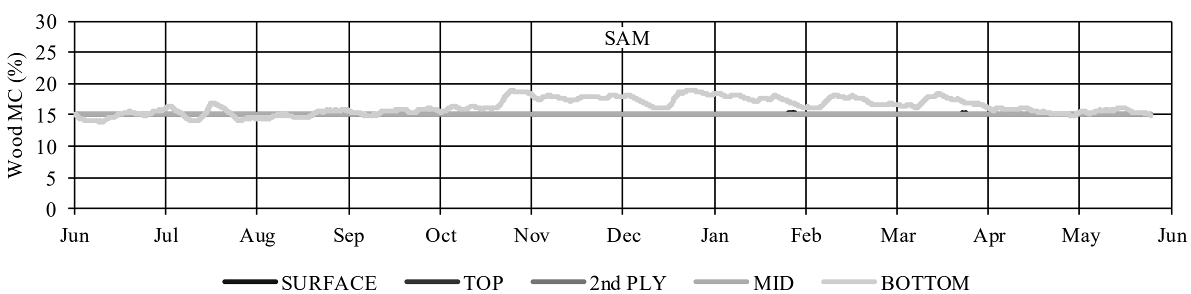


Figure 14: Predicted Performance – SAM coating, starting moisture content <15%

The impermeable membrane completely decouples the CLT performance from the screed and represents an ideal performance conditions. Only the bottom surface of the CLT is influenced by the ambient relative humidity as shown above.

In a non-ideal circumstance where the CLT is wetted prior to the installation of a coating, a degree of drying to the top is required. A starting moisture content of 25% was selected, representative of measured moisture content in the wood samples. While the screed is itself a vapour retarder, it is nonetheless *more* permeable than the CLT and will thus enable a slight degree of topside drying. Therefore, careful attention to the permeability of the water-resistant coating is required. Where lower permeable coatings are used, the upward drying ability of the CLT will be reduced, and moisture may be trapped in the CLT for extended periods. The moisture content profiles of CLT panels with moisture content above 25% and the installation of the cementitious screed on June 1st are shown in Figure 15 for uncoated CLT, CLT coated with polyurethane primer, CLT coated with silicone sealer, and CLT with SAM.

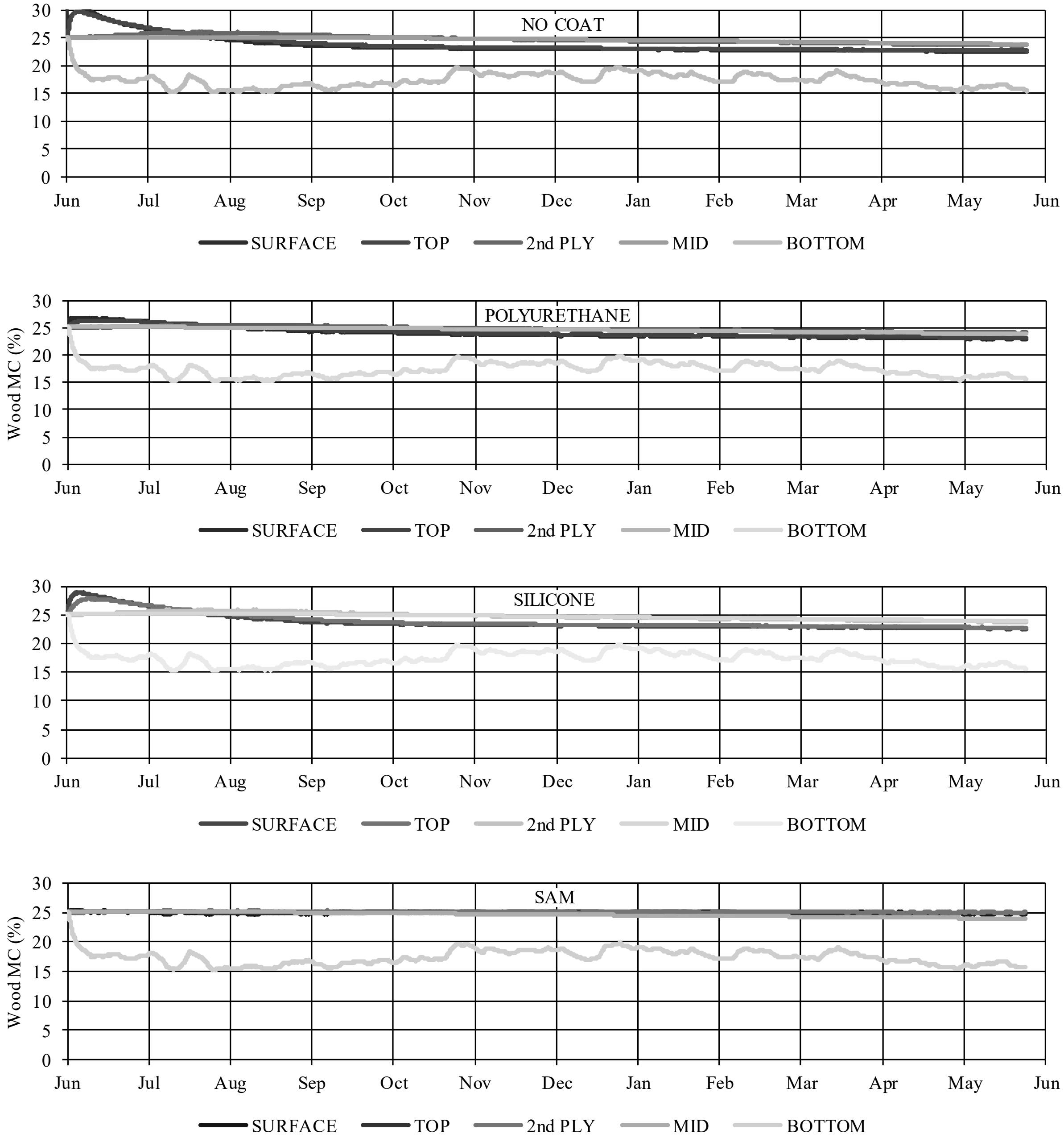


Figure 15: Predicted Performance – No Coating (Blue), Impermeable Coating (Red), and Permeable sealer (Green), and Impermeable Membrane (Brown) at starting moisture content >25%.

A scenario where the CLT is wetter than 25% MC will pose a risk regardless of the coating. However, both the polyurethane and silicone coatings eventually show a drying trend. The SAM membrane, however, does not and demonstrates the significant risk of applying an impermeable membrane to wet CLT.

Mould and Decay Predictions

To help provide more accurate analysis, the hygrothermal results will be compared using the Finnish VTT Technical Research Centre's Improved Model to Predict Mold Growth in Building Materials (Viitanen, 2007) and a Dose-Response Model for Fungal Decay (Brischke and Rapp 2008). These models are empirical regressions of actual mould and rot growth in varying climatic conditions. The VTT model does not guarantee presence of absence of mould, but provides a greater degree of reliability than common threshold limits (e.g.80% RH threshold for mould). The VTT model output is a mould index, the extent summarized in Table 1. A sensitivity class of 'sensitive' was selected to represent the planed and processed CLT panels.

Table 2: Mould Index for the VTT Model (Viitanen, 2007)

Index	Growth Rate	Description
0	No growth	Spores not activated
1	Small amounts of mold on surface (microscopic)	Initial stages of growth
2	<10% coverage of mold on surface (microscopic)	–
3	10%-30% coverage (visual)	New spores produced
4	30%-70% coverage (visual)	Moderate growth
5	>70% coverage (visual)	Plenty of growth
6	Very heavy and tight growth.	Coverage around 100%

The ASHRAE 160 (2016) stipulates that the maximum threshold for the mould index should be 3. The Dose-Response model uses a Mean Decay Rating from 0 to 4, which is derived from pick-tests that assesses the structural integrity of wood stakes, with description of the ratings shown in Table 3. Approximately 200 dose units are required to show slight decay. Both methods used the top-ply moisture content as the model moisture input.

Table 3: Mean Decay Rating (EN 252)

Decay Rating	Rating of Decay	Dose Units
0	Sound-no decay	0-150
1	Slight decay	150-500
2	Moderate decay	250-600
3	Severe decay	350-800
4	Very sever decay (stake fails during mechanical bending)	500+

To provide a conservative estimate for the risk of mould and decay, the 25% initial moisture content simulations were used. If these samples do not suggest risk of fungal contamination, then it is probable that scenarios with lesser degree of wetting are safe.

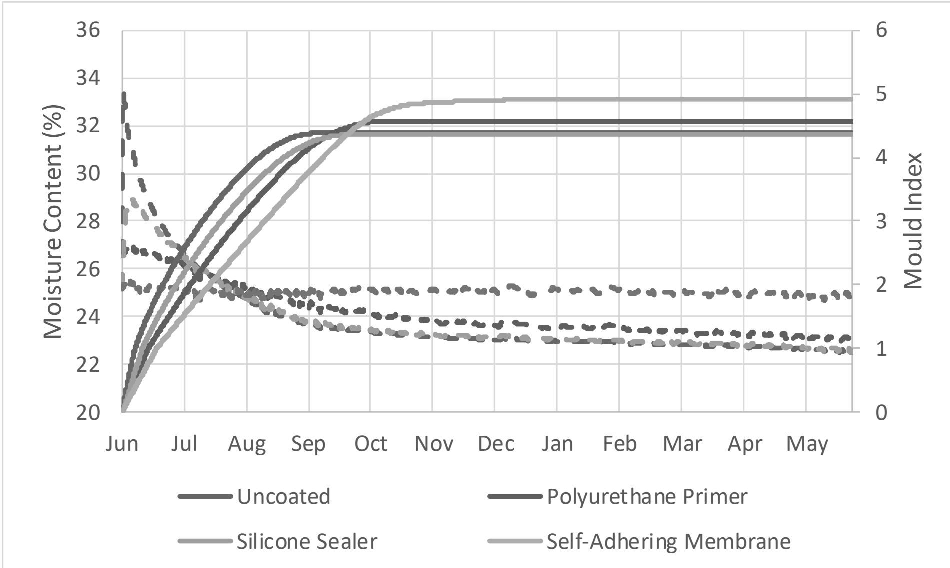


Figure 16: Moisture Content and Mould Index Scores for Uncoated, Polyurethane, Silicone, and Self-Adhered Membrane Coatings

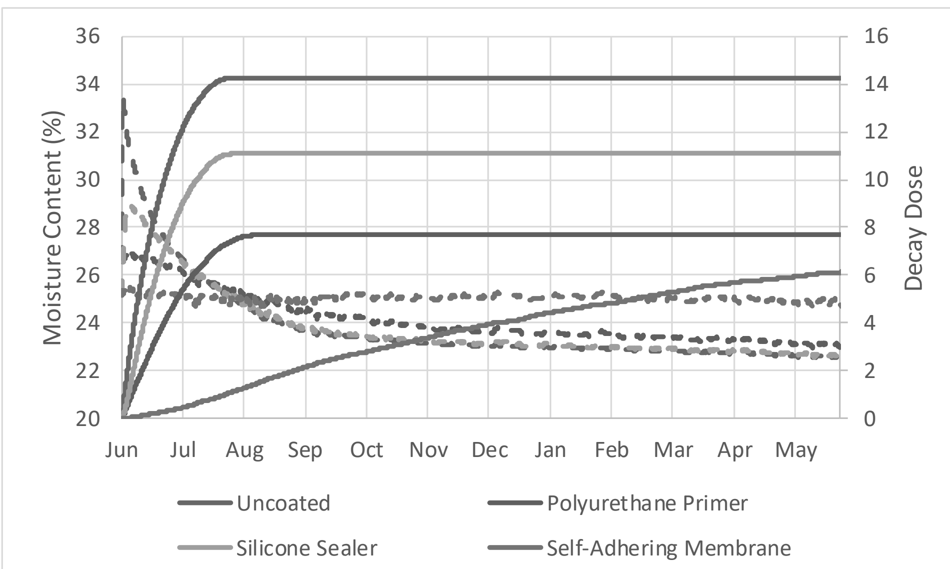


Figure 17: Moisture Content and Mean Decay Dose for Uncoated, Polyurethane, Silicone, and Self-Adhered Membrane Coatings

The elevated moisture content suggests high likelihood of observing surface fungal contamination (mould index greater than 3 for all four configurations) on all substrates starting at 25%MC, as determined by the VTT model. Removal of the cementitious topping of the floor mock-up confirms the presence of fungal growth at several locations. However, the extent of growth was not as high as would be suggested from the VTT model. This reduction may be due to inhibitory effects of the screed (inadequate pH). The Dose-Response results show that the high initial moisture content of the uncoated samples result in a higher dose value than the coated samples. Over the monitored period, the self-adhered membrane slowly increases in the decay dose, but begins to taper off after the simulated year. The highest dose predicted is 14 units, which is well below the threshold of 150 dose units to the start of minor decay. Even the uncoated CLT, with 25% maximum starting moisture content, does not appears to be at risk of decay provided that efforts are made to promote drying.

CONCLUSION

Due to the moisture sensitivity of CLT, careful attention to moisture sources is essential. Construction moisture, by way of precipitation or cementitious screed toppings, can subject CLT panels to significant amounts of moisture. The abundant storage capacity of CLT combined with its relative vapour impermeability over its thickness render it susceptible to biodeterioration if the moisture content threshold is surpassed for a sufficiently long duration. Generally, moisture contents above 26-28% MC (near fiber saturation) pose risks of structural decay, whereas moisture contents above 20% MC can harbour mould growth. Ideally, the moisture content of the wood should never exceed 20% in service. Investigation into the effects of factory installed water resistant coatings were a critical component of this research. Three different coatings were considered in the in-depth analysis, as prompted by the measured data:

- Permeable and hydrophobic coating, such as a silicone penetrating wood sealer,
- Low permeability coating, such as a polyurethane coating, and
- Impermeable, waterproof coating, represented by self-adhered membranes.

CLT mock-ups were created to assess the effects of precipitation and cementitious toppings with these water-resistant coatings. These mock-ups were instrumented with moisture content sensors to infer their risk of mould and rot. It was found that the samples do exceed the fiber saturation point, in some instances, for many months. Hygrothermal models were then calibrated to these two CLT experiments. The models were then used to infer long-term performance under worst-case condition. Interpretation of the hygrothermal models was completed by using the VTT Mould Index and the Dose-Response Model for Decay. The VTT Mould Index suggests a high probability of growth, evidenced by fungal contamination on some CLT samples. However, not all samples exhibited fungal growth, as this is suspected to be caused by an insufficient pH for fungal germination.

RECOMMENDATIONS

The following recommendations should be considered for the CLT panels after manufacturing and during construction:

1) Protect the CLT from external moisture during transport and handling, especially on the truck shipment from the factory to the storage and to site. On site, the CLT should be protected from all moisture sources as much as possible and well ventilated to promote drying.

2) Use active moisture management strategies and immediately remove any liquid water found on the surface of the coated CLT panels as the floors are being erected and exposed to weather. Use vacuums, squeegees and/or absorbing material where necessary. Water left on the surface poses a substantial risk of wetting CLT panels. Continual review of all floors during construction will be required during the entire construction phase as liquid water at the top exposed floor can migrate down at openings and intersections to lower levels.

3) Do not rely on passive moisture management strategies such as attempting to seal the CLT panels or the screed topping from the top side. Moisture is likely to penetrate through joints in the CLT and cracks in the screed topping, and at edges and penetrations in the floor.

4) Consider using preservative treated non-CLT wood accessories such as plywood splines. These smaller items have less moisture storage capacity and may be at a higher risk of moisture uptake, and may not have the same re-distribution qualities as the CLT structure.

5) Install the screed topping on dry CLT panels with a measured moisture content of less than 15% MC. Use non-moisture producing construction heaters (e.g. electric) as necessary to promote drying of the CLT panels.

6) Keep the floors well ventilated after the screed topping is placed to allow continual drying of the screed and the moisture that may have entered the CLT panel. Employ the same moisture management strategies for the top surface of the screed topping as used for the exposed CLT panels.

These recommendations highlight the care and planning needed to achieve the intended protection of the CLT using coatings and active moisture management strategies. Attention must extend from the manufacturing stage at application, through CLT construction and placement of the screed topping, to the full enclosure of the building.

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Appendix A: Hygrothermal Material Properties