Wetting and Drying Performance related to On-site Moisture Protection of Cross-Laminated Timber

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When a CLT edge was directly exposed to intense rain for three months, an end grain sealer was found to be the most effective among the three water repellents assessed to prevent wetting. For more severe wetting conditions, it is expected that a self-adhered vapour-permeable membrane would be best to prevent water penetration from exposed end grain but also to maintain the drying capacity.

When uncured wet concrete topping (a product of self-leveling floor screed) was placed on CLT, negligible moisture from the concrete penetrated in the CLT below. Although the two types of membranes tested reduced moisture interaction between the wood and the wet concrete, the most practical protection is probably to keep the wood reasonably dry (e.g., with a moisture content of CLT below 16%) by sheltering it before and after installing concrete topping to minimize the moisture risk.

When an edge of untreated CLT sat on damp concrete for three months, the moisture uptake from the concrete caused considerable wetting. A damp-proof treatment is needed to reduce the moisture risk. Among the two water repellents tested, the end grain sealer kept the moisture content at two measurement locations largely below 15%.

Regarding the impact of a fire-proof covering on the drying performance of CLT, it was found that 25 mm thick mineral wool insulation did not appear to impede drying, while one layer of drywall reduced the drying rates by about 20%, and three layers of drywall reduced the drying rates by about 50%, compared to the CLT control specimen without any surface covering. However, only 40% of the moisture gained during the initial wetting period evaporated from the uncovered CLT control specimen over a period of two months under sheltered conditions. This suggests that natural drying cannot be relied upon and that the wood should be kept dry before and after being covered with other materials, particularly in the winter in coastal areas.

Implications for moisture protection practices based on the test were summarized at the end of this report.
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1 OBJECTIVES

- To investigate the wetting and drying behaviour of the face and edge surfaces of cross-laminated timber (CLT), including edge-to-edge joints covered with plywood spline
- To evaluate effectiveness of water-repellent coatings and membranes that are factory-applied with the intent to prevent wetting caused by rain, installation of wet light-weight concrete topping, or contact with damp concrete surfaces
- To assess potential impact of fire protection measures including drywall and rigid mineral wool insulation on the drying performance of wet CLT
- To further develop practical solutions for on-site moisture management of mass timber construction

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3 INTRODUCTION

In recent years cross-laminated timber (CLT) has been increasingly used in both residential and non-residential construction in North America, particularly in buildings taller and larger in size than mid-rise wood frame buildings. As a mass timber material, CLT offers many advantages compared to traditional wood products, such as dimension lumber and solid-sawn timbers, particularly where larger storey heights or longer spans are required. However, similar to traditional wood products, CLT may develop staining, mould, and even excessive dimensional changes and decay, when it is exposed to prolonged dampness (Wang 2016a). According to the ANSI/PRG 320 Standard for Performance Rated CLT, CLT is intended to be used only under dry service conditions1 (ANSI and APA 2012); however, as a structural product it is required to possess sufficient moisture resistance to withstand temporary wetting during construction or “other conditions of similar severity”. In terms of moisture control, the construction stage is likely the most challenging given the wide range of possible exposure conditions and the inevitable site and cost constraints (Gagnon and Pirvu 2011; Karacabeyli and Douglas 2013; StructureCraft 2015; FII and BSLC 2014; Wang 2016b; WoodWorks 2016; Structurlam 2017). Previous studies and experience have shown that mass timber products such as nail-laminated timber (NLT) and CLT tend to dry slowly once wetting occurs and there

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1 “Dry service” conditions means wood is used under conditions where the equilibrium moisture content should average about 16% or less over a year. This typically can be achieved under an unheated open shed. In an indoor climate controlled environment, the average moisture contents are lower and less variable.
is a need for on-site moisture protection, particularly in a wet climate (Wang 2014; Wang 2016c; Wang 2016d). On the other hand, moisture is generally slow to penetrate into CLT made with Canadian softwoods, which are mostly resistant to water penetration (Lepage 2012; Alsayegh et al. 2013; McClung et al. 2014; Wang 2014; Wang 2016c; Wang 2016d; CWC and FPInnovations 2017).

The UBC Tall Wood House (Brock Commons) building greatly showcases the use of mass timber or CLT in a high-rise building. Just like other large mass timber buildings, this project received major concerns about construction moisture when it was started. The design and construction team therefore developed strategies and applied a series of measures to prevent wetting from the manufacture through the construction phase. The major measures included use of off-site fabrication to minimize site work, covering panels with a plastic wrap during the transportation, just-in-time delivery to eliminate the need for site storage, actively removing standing water from installed floors after rain events, and installing upper floors, exterior walls, and the roof quickly to protect the interior structure. These measures worked out satisfactorily and effectively reduced the time of exposure to rain. Also, most of the interior structural framework was erected during the drier summer months that greatly enhanced the drying potential. Field measurements showed that the average moisture content (MC) about 6 mm deep below the surface of the CLT floor panels remained below 20% during periods of rain while the building was under construction (Wang and Thomas 2016; Mustapha et al. 2017).

A field test was conducted on a mock-up of structure and materials to be used in the UBC Tall Wood House building by the project building envelope specialist, RDH Building Science Inc., to assess the effectiveness of several commercially available water-resistant coatings in preventing wetting caused by rain or wet concrete topping (RDH 2016; Lepage et al. 2017). It was found that installing a water repellent slowed down overall water penetration, and that the low-permeance coatings and a type of self-adhered impermeable membrane tested showed the best effectiveness. For the UBC Tall Wood House project, a water repellent was factory-applied on the top surface of CLT floor panels. At the site, panel joints and service holes were sealed using tapes to prevent water from dripping onto lower floors. But as expected, rainwater found its way through the gaps between boards of CLT; from joints, water also migrated into plywood spline and into the wood by the exposed end grain. Before pouring wet concrete topping, another water repellent was applied on the floors to reduce water penetration from the concrete.

Taking into account the experience from the UBC Tall Wood House project, this study aimed to generate further information about wetting and drying behaviour of CLT and the effectiveness of applying water repellent coatings and membranes in preventing potential wetting during construction based on existing knowledge and experience. Water repellents, alone or together with preservatives or stains have been commonly used on exterior wood, such as decks and fences to reduce water absorption and to slow down weathering (Williams and Feist 1999). In terms of applying temporary moisture protection measures, engineered wood products including CLT are typically wrapped with plastic sheets to prevent wetting during shipping. Factory-applied water repellent on edges and even on wide surfaces is becoming common as a
temporary site protection measure and also a value-added step. In the marketplace, wood-based composite panels integrated with a membrane/coating, which may function as a water- and air-resistive sheathing membrane in service of exterior walls\(^2\) have become available. It is anticipated that the test results of this study will help facilitate wider adoption of effective on-site moisture protection measures not only by design/construction professionals, but also by manufacturers of CLT and other wood products using factory-applied water repellants.

For a specific construction project, the wetting and durability-related risk, protection needs, and costing for different levels of on-site protection should be assessed in advance to make informed decisions, based on climatic conditions anticipated during construction, and the materials and assemblies used. Given the uncertainty, particularly regarding climatic conditions and work stoppages, potential remediation efforts and additional moisture-risk mitigation measures should also be on hand. In contrast to the measures investigated in this study, alternative methods, such as temporary roofs, have been used in Europe for a number of large timber building projects to protect wood through the entire construction (FII and BSLC 2014). Standards on on-site moisture management and other aspects of quality assurance have been developed, led by Finland (Finnish Standards Association 2012). The Finnish standard requires that the construction company develop a moisture control plan and an assembly plan for wood materials used for load-bearing structures in coordination with manufacturers and designers. Both plans should include the expected level of on-site protection based on the design MC of wood. That includes, if the in-service MC is below 15% (which would include almost all wood elements in a conditioned indoor space), that the expected protection level would be Protection Level 3, which requires indoor conditions or a heated tent for construction. Such requirements are certainly a large step up in terms of both effectiveness and costs, compared to the pre-treatment measures dealt with in this study.

4 BACKGROUND

Theoretically the effectiveness of a moisture protection measure in preventing wetting depends on both its water repellency efficiency and vapour permeance. The major function of a water repellent\(^3\) is to slow the uptake of liquid water through the use of chemicals, such as wax (Williams and Feist 1999). It can also slow down the exchange of water vapour (i.e., adsorption or desorption) between wood and the surrounding atmosphere, depending on vapour permeance of the coating formed. Coatings can have a wide range of vapour permeance, depending on their formulations and thicknesses etc. (see some measurement results of vapour permeance of coatings on wood in Schniewind and Arganbright (1984) and Pavlic and Petric (2015)). No water repellent coating used on wood is known to be completely impervious to water vapour. Similarly, membrane products also vary in both water resistance and vapour permeance. Among commonly used products, the membranes installed on exterior walls of wood-frame construction as the water-resistive barrier, including loose sheets, self-adhered,

\(^{2}\) One example is available at http://zipsystemrevolution.com

\(^{3}\) Beading of water was visible on most water repellent-treated specimens after rain when the outdoor exposure started. Fewer specimens showed beading after three months’ exposure. See photos in Appendix III.
and liquid-applied membranes are typically relatively thin, have high vapour permeability to allow drying towards the exterior, and offer adequate protection against rain penetration when bulk water is allowed to drain away. Most of those products are not expected to resist long- or even short-term water ponding for horizontal applications. For example, water penetration through two loose sheet products\(^4\) was observed in a previous study when they were installed on horizontal surfaces as a potential moisture protection measure (Wang 2016c; d). By comparison, adhered roofing membranes installed on low-slope roofs are typically thick, heavy-duty, and have high resistance to both water penetration and vapour transmission.

This study aimed to provide general trends of MC changes under test conditions selected to represent a severe wetting event prior to sealing the assembly, with a primary interest in identifying both the potential moisture risk and the protection solutions. A literature review about the critical MCs of wood arising from moisture introduced during construction that would likely lead to durability-related issues is reported in Wang (2016a). Overall the risk will be high when the MC is close to or above the fibre saturation point (i.e., 30%). A MC of 26% was found to be the critical MC for initiating decay when other conditions (e.g. temperature, untreated wood) were favourable for fungal growth; under such marginal moisture conditions, it would take several months for decay to initiate (Wang et al. 2010). However, decay and consequent strength loss can occur rapidly (e.g., in weeks in susceptible wood species), when there is a larger amount of free water available with a MC ranging from 40% to 80%. Compared to decay, mould or staining does not affect wood strength. Mould growth is more associated with the relative humidity of the environment, more specifically, the surface relative humidity (sometimes called “water activity”) of the building components. It needs a minimal relative humidity of around 80% to grow on wood at a temperature of 20-25°C, corresponding to an equilibrium MC of wood of 16%; under such marginal conditions, it could take months or longer for mould to initiate on wood materials (Nielsen et al. 2004).

5 **SURVEY RESULTS**

To help develop a more targeted test plan for this study, a small survey was conducted to gather feedback from building envelope engineers, contractors, and manufacturers. The results are summarized below in this section.

Interest expressed by building envelope engineers\(^5\) include:

- Demonstrating the need for moisture protection, for end grain and panel joints in particular

- Comparative information on the effectiveness of a range of water repellents and membrane products to preventing CLT wetting during construction and potentially in building service

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\(^4\) One is a building paper product and the other is a vapour-permeable spun-bonded polyolefin sheet.

\(^5\) With input from RDH Building Science Inc. and Morrison Hershfield Ltd.
Interest and concerns raised by contractors include:

- How much wetting is too much and how long it takes for CLT to get wet and to subsequently dry out. Such basic information is required to better assess the needs and to develop on-site moisture protection measures in the coastal climate of British Columbia.

- How effective are water repellents or membranes? Are they compatible with subsequent procedures, such as installation of wet concrete topping and finishing with coating?

- Applying water repellent or installing a membrane on site often complicates and delays construction.

- Installing a self-adhered impermeable membrane on dry CLT in the factory may require coordination with a professional roofer; the joints between panels should be immediately sealed after installation to prevent moisture ingress. The use of an impermeable membrane on wood requires extra caution since it eliminates the drying capacity.

- A moisture protection measure that makes a horizontal surface (e.g., floor, roof) slippery creates a construction safety hazard.

- In addition to concern about moisture, colour change (so-called “sun tanning”) resulting from exposure to UV may also require attention, particularly for timber members to be exposed in service for appearance.

Manufacturers of engineered wood products often provide guidance for on-site lifting, handling, and weather protection (Structurlam 2017). The CLT manufacturers surveyed have the following concerns about pre-treatment of CLT in factory:

- The cost for applying a protective water repellent/membrane on CLT may compromise its competitiveness, especially when the treatment is not a mandated standard practice, or if the benefit is not well known or documented.

- Spraying water repellent requires extra safety and environmental measures (e.g., related to VOCs), and capital investment.

- Treating the wide surfaces of CLT in factory requires a large work space, which may not be readily available, particularly when a water repellent requires a long time (typically from hours to days) to cure.

6 MATERIALS AND METHODS

6.1 Materials and Tests Setup

The CLT specimens used in this study were provided by a Canadian manufacturer. To capture as much variability in the product as possible within the timeframe of the project, thirty 3-ply panels, measuring 400 mm × 400 mm × 87 mm (thickness) were collected from trimmings from

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6 With input from Urban One Builders and Nicola Logworks
factory production over a period of three months. The CLT complies with the APA/ANSI PRG-320 standard and was made from visually graded Spruce-Pine-Fir (S-P-F) lumber and bonded with a polyurethane adhesive. The specimens arrived in the FPIinnovations laboratory in early July and were then kept in a conditioning chamber to maintain a MC of about 15% before treatment. This is consistent with the results of field measurements from the UBC Tall Wood House project, where an average MC of the CLT floor panels was found to be about 15% at the time of installation (Wang and Thomas 2016).

These CLT specimens were tested in six groups for different purposes (Table 1). The major focus of the study was to assess effectiveness of water repellents and membranes pre-installed on the CLT panel wide face (i.e., concerning water penetration in the transverse grain orientation) or the CLT panel edge (i.e., concerning water penetration in both the transverse grain orientation and the longitudinal direction through end-grain). The reasons for providing this moisture protection is to prevent wetting and subsequent absorption of water from rain, wet light-weight concrete topping, or a damp concrete slab. Three groups of CLT specimens were exposed to the rainy wintertime weather in the rear yard of FPIinnovations’ Vancouver laboratory, starting October 24, 2017 (see weather conditions in Appendix I), after each test surface was treated with a water repellent or covered with a membrane (See Appendix III for photos taken during preparation of test specimens). Configurations of these test specimens included horizontal surfaces without any joint (Group 1, Table 1), horizontal surfaces with a butt joint covered with plywood spline (Group 2), and vertical setup with the top edge exposed to weather (Group 3). The CLT joint was created by removing with a router a slot, measuring 19 mm deep and 150 mm wide, down the center of the panel face and along the grain of the top lamina. The CLT specimen was then cut into two pieces to create a butt joint along the centerline of the slot. The slot was then filled with a piece of plywood spline (Canadian Softwood Plywood, 19 mm thick and 150 mm wide) and fastened with four screws (Appendix III, Figure 47).
In addition to the testing under natural exterior conditions, Group 4, 5, and 6 were set up in a shed to simulate sheltered exterior conditions, typical of new construction. The shed was covered but open to the exterior on one side, without any space heating or mechanical ventilation. Group 4 was used to assess the impact of pouring wet light-weight concrete topping on a CLT wide surface to simulate the scenario often experienced by a floor or a flat roof (Figure 2; Error! Reference source not found.). The concrete installed was a light-weight self-leveling product commonly used on wood-based floors to improve sound isolation and fire safety. After the wood surfaces were slightly wetted, the wet mix of concrete was immediately poured on the test specimens to a thickness of 40 mm, based on the mixing and installation instructions provided by the concrete manufacturer. Group 5 was set up to assess moisture absorbed through an edge of CLT in contact with damp concrete below, simulating a scenario of a CLT wall sitting on a concrete slab (Figure 3Error! Reference source not found.). Three CLT specimens, with or without water repellent treatment on the bottom edge, sat on the same block of concrete paver, which was placed in a container located in the shed. The bottom (about half of its thickness) of the concrete block was submerged in water to maintain dampness throughout the test. With Group 6, the four CLT specimens were first placed horizontally exterior so that the wide face would be exposed to weather (i.e., rain, sun) for about a month to simulate typical construction wetting in this climate. The wetted top surface was afterwards covered with either one or three layers of 12 mm drywall, or rigid mineral wool insulation with a thickness of 38 mm before the specimens were placed on a shelf in an open shed to assess drying rates (Figure 4Error! Reference source not found.).
Figure 2  CLT and reference specimens kept in a shed for observing drying rates after wet concrete topping was installed on the top surface

Figure 3  CLT specimens sitting on damp concrete in a shed to observe wetting through the bottom edge
In total, seven water repellent products were evaluated in this study as potential on-site water protection measure (Table 2). These products were chosen since a number of them had been used by manufacturers of engineered wood products or contractors as a temporary moisture protection measure. The selected products also covered a range of formulations with different active compounds. WR No. 1 and WR. 6 were purchased from a building supply store and the other five products were supplied by two manufacturers. Being a commonly used and economical product, Thompson’s Water Seal, advanced (TWS) was used in this study as a benchmark treatment; it was applied on-site to the CLT floors of the UBC Tall Wood House project. No. 2 was specified to treat CLT floor panels in the factory for the same project. No. 3 has been used on LVL by a large manufacturer. No. 3, 4, and 5 had similar formulations but with an increased concentration of the effective compound (i.e., wax) from No. 3 to No. 5. No. 6 is a thick polyurethane exterior-rated coating for providing aesthetic appearance and improving water resistance. No. 7 is a recommended product for sealing end grain of wood products to reduce checking. The application of these coating products was conducted by the same technologist to ensure consistency. Each water repellent was generously brush-applied to the wood surfaces with one coat and then allowed to fully cure prior to the exposure test. Together with water repellents, two types of self-adhered membranes, labelled as MEM No. 1 and MEM No. 2 were evaluated. They were to represent vapour permeable and impermeable products, respectively, with large differences in vapour permeance and water resistance. In addition, a

7 The water resistance of a membrane product is typically tested using the “boat” test method (ASTM D779, ASTM 2003) or the “hydrostatic head” method (AATCC 127, AATCC 2014) related to exterior wall applications (Holladay 2011). The Canadian Construction Materials Centre (CCMC) developed a “water ponding” test (which was summarized in “Technical Guide for Sheathing, Membrane, Breather-Type”, but the detailed reference was not
type of loose plastic lumber wrap, typical of the most commonly used membrane in the wood industry to protect dry wood products during shipping, was tested on one CLT specimen. Each membrane was stapled to the edges of each specimen, covering the top surface without any penetration. It should be noted that although the study did not include any physical abuse of the membrane, a self-adhered membrane would be expected to better withstand the wear and tear during construction, and should provide better protection, compared to a loose wrap.

Plywood (Canadian Softwood Plywood, 19 mm thick), OSB (18 mm), and NLT were included in this study (Table 1) as reference specimens. Each NLT specimen was built by nail-laminating five 400 mm long, 38 mm × 140 mm S-P-F boards and then covering the top edges of the boards with 19 mm thick plywood. The wetting and drying behaviour of these products has been extensively studied (Wang 2014; Wang 2016c; Wang 2016d). Except for Group 1 where two control specimens (i.e., exposed without any protective measure) were provided, the expanded scope of the project given the resources available permitted only one specimen without replication under all test conditions. As the specimens were small relative to panels typically specified, it was important to limit the wetting and drying primary to one major direction. To achieve this, each CLT, plywood, and OSB specimen was sealed using two coats of epoxy (Intergard 740, a two part epoxy finish) as a standard practice in the lab, either on the four edges when a wide surface was to be treated and tested, or on the two wide surfaces and two edges when an edge (of CLT) in the other direction was to be treated and exposed. Additional self-adhesive impermeable membrane was used to seal the four edges of assembled specimens, including the CLT specimens covered with fire-rated gypsum (i.e. the fire safety measure) and the NLT specimens covered with plywood. The exception for sealing was the CLT specimens with a butt joint covered with plywood spline: none of the exposed edges of the CLT or the plywood at the joint was sealed or treated, which is typical construction practice.

Table 1 Summary of test variables*

<table>
<thead>
<tr>
<th>Wood specimens</th>
<th>Protection measures assessed</th>
<th>Wetting and drying condition</th>
<th>Number of specimens</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Water repellent</td>
<td>Membrane</td>
<td></td>
</tr>
<tr>
<td>Group 1, test purpose: in horizontal setup with the top wide surface exposed to weather, to assess the effectiveness of water repellent/membrane in preventing wetting</td>
<td></td>
<td>Outdoor exposure after water repellent/membrane was installed</td>
<td>11</td>
</tr>
<tr>
<td>CLT</td>
<td>TWS**</td>
<td>Lumber wrap</td>
<td></td>
</tr>
<tr>
<td></td>
<td>WR No. 2</td>
<td>MEM No. 1, a permeable membrane</td>
<td></td>
</tr>
<tr>
<td></td>
<td>WR No. 3</td>
<td>MEM No. 2, an impermeable membrane</td>
<td></td>
</tr>
<tr>
<td></td>
<td>WR No. 4</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>WR No. 5</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

found). When a membrane passes this test based on the guidelines developed by CCMC, it is able to resist water penetration for 2 hours in a depth of water of 25.4 mm. The vapour permeance of a material can be tested based on ASTM E98 (ASTM 2013).
<table>
<thead>
<tr>
<th>Wood specimens</th>
<th>Protection measures assessed</th>
<th>Wetting and drying condition</th>
<th>Number of specimens</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Water repellent</td>
<td>Membrane</td>
<td></td>
</tr>
<tr>
<td>Reference, plywood</td>
<td>TWS</td>
<td>MEM No. 1</td>
<td></td>
</tr>
<tr>
<td>Reference, OSB</td>
<td>TWS</td>
<td>MEM No. 1</td>
<td></td>
</tr>
<tr>
<td>Reference, NLT with plywood</td>
<td>MEM No. 1</td>
<td>MEM No. 2</td>
<td></td>
</tr>
</tbody>
</table>

**Group 2**, test purpose: in horizontal setup with the top wide surface including plywood spline exposed to weather, to assess the effectiveness of water repellent/membrane in preventing wetting

| CLT with a butt joint covered with plywood spline | TWS | MEM No. 1 | Outdoor exposure after water repellent/membrane was installed | 3 |

**Group 3**, test purpose: in vertical setup with the top edge exposed to weather, to assess the effectiveness of water repellent/membrane in preventing wetting

| CLT | TWS | MEM No. 1 | Outdoor exposure after water repellent/membrane was installed | 4 |

**Group 4**, test purpose: in horizontal setup in a shed, to assess the impact of wet concrete topping on wetting and drying

| CLT | TWS | MEM No. 1 | One CLT specimen was wetted exterior for a month before concrete topping was installed | 5 |
| Reference, plywood | TWS | MEM No. 1 | Drying in a shed after wet concrete topping was installed. | 3 |
| Reference, OSB | TWS | MEM No. 1 | One CLT specimen was wetted exterior for a month before concrete topping was installed. | 3 |
| Reference, NLT with plywood covering | MEM No. 1 | | | 2 |

**Group 5**, test purpose: in vertical setup with the bottom edge of CLT sitting on damp concrete in a shed, to assess the effectiveness of water repellent/membrane in preventing rising moisture

| CLT | TWS | MEM No. 1 | Edge sitting on damp concrete in a shed | 3 |

**Group 6**, test purpose: to assess the effect of a potential fire safety measure on drying in a shed, after the CLT specimens exposed to weather for about a month

| Fire safety measures assessed | Wetting and drying condition |  |
|------------------------------|------------------------------|  |
| Drywall, 1 layer, 12 mm      | Drying in a shed, after wet surface was covered with drywall or mineral wool | 4 |
| Drywall, 3 layers            |                              |  |
| rigid mineral wool insulation, 38 mm |                              |  |

**In total** 49
*Untreated control specimens (CLT, plywood, OSB, and NLT) without any covering were provided for each group.
** "TWS" stands for Thompson Water Seal, advanced.

### Table 2  Materials used in this study in addition to wood products

<table>
<thead>
<tr>
<th>Product label used in the report</th>
<th>Product description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Water repellents evaluated</strong></td>
<td></td>
</tr>
<tr>
<td>TWS*</td>
<td>A combination of alkyl polysiloxane resin and hydrophobic waxes, water-based</td>
</tr>
<tr>
<td>WR No. 2</td>
<td>A clear, penetrating sealer for wood products based on alkyd urethane</td>
</tr>
<tr>
<td>WR No. 3</td>
<td>A water-based wax emulsion sealer formulated specifically for engineered wood products, in a low concentration</td>
</tr>
<tr>
<td>WR No. 4</td>
<td>A water-based wax emulsion, in a medium concentration</td>
</tr>
<tr>
<td>WR No. 5</td>
<td>A water-based wax emulsion, in a high concentration</td>
</tr>
<tr>
<td>WR No. 6</td>
<td>A thick concentration of polyurethane for exterior use</td>
</tr>
<tr>
<td>WR No. 7</td>
<td>A thick concentration of modified hydrocarbon wax, an end grain sealer</td>
</tr>
<tr>
<td><strong>Membranes evaluated</strong></td>
<td></td>
</tr>
<tr>
<td>MEM No. 1, a permeable membrane</td>
<td>A self-adhesive vapour permeable air barrier, with vapour permeance of 629 ng/Pa•s•m² (11 perm) based on a dry cup test and 972 ng/Pa•s•m² (17 perm) based on a wet cup test (ASTM E96)</td>
</tr>
<tr>
<td>MEM No. 2, an impermeable membrane</td>
<td>A self-adhesive impermeable membrane, together with a prime</td>
</tr>
<tr>
<td>A lumber wrap</td>
<td>A reused plastic membrane, which is typically used for wrapping dimension lumber and engineered wood products. Its vapour permeance is estimated to be around 1500 ng/Pa•s•m² (25 perms).</td>
</tr>
<tr>
<td><strong>Other materials used</strong></td>
<td></td>
</tr>
<tr>
<td>Concrete topping</td>
<td>Cement, aggregate, admixture, and water, with mixing and installation instructions provided by the manufacturer</td>
</tr>
<tr>
<td>Rigid mineral wool insulation</td>
<td>A rigid mineral wool in thickness of 38 mm (1.5 in.), with thermal resistance of R-6), with vapour permeance of about 1768 ng/Pa•s•m² (31 perm) based on a dry cup test</td>
</tr>
<tr>
<td>Drywall</td>
<td>Paper-faced drywall, 12 mm (1/2 in.) in thickness, with vapour permeance of about 1000 ng/Pa•s•m² (17 perm) based on a dry cup test</td>
</tr>
</tbody>
</table>

""TWS" stands for Thompson Water Seal, advanced.

#### 6.2 Instrumentation and Measurements

Two types of resistance-based moisture pin sensors were used in this study: long and thick pins for measuring MC in solid wood including the boards in the CLT and NLT specimens, and a type of much shorter and thinner moisture sensors for measuring MC in the plywood and OSB
generally remained intact; however, in spite of pre-drilling of each hole, the coating on the short pins was easily damaged which meant moisture readings could be influenced by moisture elsewhere along the length of the pin. Most CLT specimens received two pairs of long pins through their bottom surfaces (Figure 5). One sensor was installed about 6 mm deep below the top surface to measure surface MC of the top central board and the other was installed about 12 mm deep in the same board to measure central MC. In each plywood or OSB reference specimen, two pairs of short moisture sensors were installed in a similar manner, measuring the surface MC (i.e., defined as MC in the top ply of plywood, and 6 mm below the top surface of OSB) and the central MC (i.e., found at mid-depth), respectively (Figure 6). In the built-up specimens including the CLT specimens with a butt joint and plywood spline, and the NLT assemblies with plywood covering, sensors were installed in both the solid wood and the plywood. For example, in the CLT specimens with spline, two pairs of long pin sensors were installed in the middle lamina of the CLT to detect moisture changes in the longitudinal direction: one pair 12 mm and the other pair 25 mm away from the end grain at the joint; a third pair of sensors was installed in the top layer, about 25 mm away from the edge but in the transverse direction (Figure 7). Two additional pairs of sensors were installed in the plywood spline to assess moisture changes in its top and bottom surface, respectively. In each NLT specimen, two pairs of long moisture pin sensors were installed in the middle board to measure the MC in its top surface just adjacent to the plywood, and at mid-depth; and one pair of short pin sensor was installed in the top surface of the plywood (Figure 8). In each vertical CLT specimen configured to assess moisture uptake through its edge, two pairs of long pin sensors were horizontally inserted into the top lamina, one 12 mm and another 25 mm away from the end grain, respectively, to measure MC changes in the longitudinal direction; and one pair of sensor was installed in the middle lamina 25 mm away from the edge to measure MC change in the transverse grain orientation (Figure 9).

In total, 108 pairs of moisture sensors were installed in these 49 test specimens. Measures were taken during the installation to ensure consistency in the installed depth of pins for each target depth of measurement. To ensure that no sensors penetrate any test surface, coating or membrane, the pins were installed from underneath when the top surface was to be measured. The gap between each pin and its entry point into the wood member (from the unexposed side) was sealed with water-resistant sealant. External connectors were provided for each pair of moisture pins so that its MC readings could be taken conveniently using a moisture meter. Given the use of mixed wood species for the products used in this study, the readings were left unadjusted and based on the default wood species, which is Douglas fir at a temperature of 21°C. Readings were collected manually every week, together with the weight of each specimen. For the specimens with wet concrete topping installed, specimen weights were not monitored and only MCs from the pre-installed sensors were recorded.
Figure 5  A CLT specimen with two moisture pin sensors installed at two depths to measure moisture changes in the top central board for Group 1, 2, 4, and 6.

Figure 6  A plywood or OSB specimen with moisture pin sensors installed to measure moisture changes in the top surface or at middle depth for Group 1 and 4.
Figure 7  A CLT specimen with a butt joint covered with plywood spline having moisture pin sensors installed in both CLT and plywood to measure moisture content at different locations for Group 2

Figure 8  A nail-laminated timber specimen with moisture pin sensors installed to measure moisture changes in the middle board (in its top surface and centre) and plywood covering (in its top ply) for Group 1
Figure 9  A CLT specimen for testing its edge, with moisture pin sensors installed in the first lamina to measure moisture change in the longitudinal direction, and in the middle lamina to measure moisture change in the transverse grain orientation for Group 3 and 5

7 RESULTS AND DISCUSSION

7.1 Data Analysis

The results, discussions, and conclusions presented below are based on the MC readings from the pre-installed sensors and the calculated surface moisture uptake amount.

7.1.1 Accuracy of MC Meter Readings

When relying on an electrical resistance-based measurement method, it is important to note that the accuracy is best in the range from 6% to 25% and that it is challenging to measure a MC close to or higher than the fibre saturation point (30% on average for most wood species) since free water in cell lumen has little effect on the electrical properties (FPL 2010). A reading higher than 30% therefore typically has a larger measurement error. A previous calibration study indicated that resistance-based measurement methods in general had acceptable accuracy (±2.0% MC) for Douglas fir, S-P-F, and OSB under ambient conditions (Wang and Thomas 2018). That study found much larger errors in measuring the MC of plywood, and attributed the error to the phenol formaldehyde adhesive and possibly the presence of sodium hydroxide in the adhesive, which increases local electrical conductivity and consequently causes overestimation of MC; this is aggravated at high MC levels. Consequently, the MC sensor readings from plywood in this study should only be used to estimate general trends. The MC readings from some plywood and OSB specimens during the outdoor exposure (with severe
wetting) were above 50% or shown as “HI (i.e., high)” by the meter. Those readings were replaced with an arbitrary value of “50%” so that charts showing trends can be generated.

7.1.2 Calculated Surface Moisture Uptake

The surface moisture uptake is defined to be the ratio between the increased weight resulting from exposure to damp conditions and the area of each test surface (i.e., a wide surface, or an edge), expressed in kg/m². The major sources of water included rain, wet concrete topping, and damp concrete in this study; such moisture was expected to penetrate through each test surface due to both capillary flow and diffusion. In addition, the high humidity in the exterior environment was expected to contribute a small portion towards the measured moisture uptake due to adsorption and diffusion of vapour through all likely surfaces (including those sealed with epoxy); meanwhile creating unfavourable environmental conditions for drying. Wetting caused by high humidity is an overall slower process but difficult to avoid in a wet climate. Untreated wood is expected to reach a MC of about 20% after staying in the constant environment with a relative humidity of 90% long enough to achieve equilibrium (FPL 2010). This portion of moisture uptake was largely ignored in the discussions below due to the difficulty in quantification. See Appendix I for the temperature, relative humidity, and precipitation measured at the test site using a weather station, and the temperature and relative humidity measured under the open shed using a sensor. After a relatively dry first week, the total precipitation reached almost 500 mm, with rain or snow (in late December and early January) occurring more than 50% of the days during the three months of outdoor exposure. The humidity in the exterior environment (outdoor and in the shed) largely remained around 90%, which is typical of this climate.

7.2 Effect of a Protective Measure during Outdoor Exposure

7.2.1 Horizontal Surface without a Joint

7.2.1.1 Control Specimens without Treatment

The variability in moisture uptake when different pieces of wood are exposed to the same wetting conditions is a concern. To assess this, both the surface moisture uptake and the MC readings at two depths from several untreated CLT specimens were assembled after being exposed to the same weather and initial wetting conditions (Figure 10; Figure 11; Figure 12). Observed differences among these specimens would then provide insight into the variation level. These specimens included the two control specimens (CLT surface control 1 and 2) in Group 1, the control specimen (No. 13) to be installed with wet concrete topping after exposure to weather for one month in Group 4, and those in Group 6 for assessing drying rates after the initial wetting by exposure to weather for about one month. Only the two control specimens in Group 1 were exposed exterior for the entire duration of the test. The data points of these

---

6 The moisture uptake was about 1.5 kg/m² for a horizontal CLT specimen exposed exterior based on the test result when the CLT top surface was covered with an impermeable membrane (Section 7.2.1 and Table 2). This would translate into an increased MC of 4% for the entire CLT specimen provided that the moisture is uniformly distributed throughout the wood and assuming the wood has an oven-dry density of 400 kg/m³.
different specimens in the three charts appear to be reasonably close at any given time of exposure, indicating that the variations among the CLT specimens was acceptable for the purpose of showing the general wetting and subsequent drying behaviour of wood. Only “CLT surface control 1” is shown in the following charts to compare with various treatments.

The test proved again that, under realistic wetting conditions, water does penetrate into the CLT in the transverse direction, although slowly. The total moisture uptake was about 4 kg/m² after three months’ exposure to both intense rainfall and high humidity (Figure 10). The MCs measured at two depths below the top surface of these untreated CLT specimens were quite close. The MC reached about 20% after one month’s exposure and was below 25% after three months’ exposure (Figures 11 and 12). CLT behaves like solid wood. Most Canadian softwood species are known to be resistant to water penetration; other wood species may be less resistant (CWC and FPInnovations 2017). The plywood and OSB reference specimens were much more absorptive than (Figure 13), as confirmed in previous studies (Wang 2014; Wang 2016b; Wang 2018).

![Figure 10](image.png)  
**Figure 10** Surface moisture uptake of CLT during three months’ outdoor exposure
Figure 11  Measured moisture content at 6 mm below the top surface of CLT during three months’ outdoor exposure

Figure 12  Measured moisture content at 12 mm below the top surface of CLT during three months’ outdoor exposure
7.2.1.2 Effectiveness of Water Repellents for CLT Surface

One of the major purposes of this study was to assess the effectiveness of water repellents and membranes in preventing wetting during construction. When the wide surface of the CLT specimens in Group 1 was exposed to intense rain, it was found that none of the six water repellents (i.e., TWS, WR No. 2, 3, 4, 5, and 6) tested was able to considerably reduce surface moisture uptake or the MC at 6 mm or 12 mm below the top surface during three months' outdoor exposure (Figure 14; Figure 15; Figure 16). The lumber wrap tested kept the MC at 6 mm deep below 15% only for the first 20 days under the test conditions; but it overall performed better than any of the water repellents tested. By comparison, the two self-adhered membrane products performed much better. Not surprisingly, the impermeable membrane (MEM 2) was the best to prevent wetting. It kept the MC readings at both measurement depths (6 mm and 12 mm below the surface) below 15% throughout three months' exposure (Figure 15); the limited observed moisture uptake, about 1.5 kg/m² (Figure 14) suggests gain of moisture from exposure to high humidity in the exterior environment. Remarkably, the performance of the vapour permeable membrane (MEM 1) followed closely, with the measured MCs staying about 15% throughout the test. Given the general concern over the use of impermeable membrane on wood due to the eliminated drying capacity (Wilkinson et al. 2017), this study suggested that even under severe wetting conditions, such as exposed floors during construction, pre-installing a self-adhered vapour permeable membrane would provide the same level of protection without compromising drying capacity. It is important to maintain a level of drying capacity for those assemblies, in case incidental wetting occurs during construction or occupancy (e.g., water from pipe leaks or activated fire sprinklers that finds its way below the membrane). All openings, holes, and gaps in floors will certainly need to be detailed properly when using a self-adhered vapour-permeable membrane for site protection. A pre-installed self-adhered permeable membrane may also serve as temporary roofing for roof panels, provided all joints between panels are immediately sealed during installation to prevent moisture ingress. A self-adhered
impermeable membrane is probably applicable only on roof panels of a low-slope roof, which is to be covered and designed to be impermeable on the top. Under such conditions, it is still important to maintain the drying capacity from below the impermeable membrane layer towards the interior, such as by integrating an interior ventilation cavity between roof sheathing and mass timber panels, as provided in the Wood Innovation and Design Centre (Wang et al. 2016). Note this study tested only these two self-adhered membrane products. There are likely discrepancies in water resistance between different membrane products.

![Graph showing surface moisture uptake of CLT (Group 1) treated with water repellent or covered with a membrane during three months' outdoor exposure](image-url)

**Figure 14** Surface moisture uptake of CLT (Group 1) treated with water repellent or covered with a membrane during three months' outdoor exposure
Figure 15 Measured moisture content at 6 mm below the top surface of CLT (Group 1) treated with water repellent or covered with a membrane during three months’ outdoor exposure.

Figure 16 Measured moisture content at 12 mm below the top surface of CLT (Group 1) treated with water repellent or covered with a membrane during three months’ outdoor exposure.
7.2.2 CLT Surface with a Butt Joint Covered with Plywood Spline

Compared to the CLT specimen without a joint, the untreated CLT specimen in Group 2 with a butt joint covered with plywood spline had a much larger moisture uptake, approaching 10 kg/m² when the top surface was exposed to weather for three months (Figure 17). The MC measurements indicated that the untreated plywood spline quickly became soaked with water, even taking into account the inaccuracies as noted in Section 7.1.1 (Figure 18). In addition, it appeared that water penetrated deeply in the CLT’s middle lamina that has its end grain exposed at the joint. The measured MCs after 15 days’ exposure were above 30% at both 12 mm and 25 mm depths in the longitudinal direction from the exposed end grain (Figure 19). This demonstrated that the joints quickly trapped and absorbed moisture not only in the plywood spline, but also in the CLT. A parallel study (Wang 2018) found that the water absorption coefficient in the longitudinal direction was about four times that in the transverse direction for Douglas-fir and eight times for lodgepole pine, based on a 24-hour partial immersion test. Joints therefore should be a priority for moisture protection. The use of water repellent (i.e., TWS) on the top surface barely reduced moisture uptake; but it did slightly delay water penetration in the CLT through the exposed end grain. By comparison, the self-adhered vapour-permeable membrane (MEM 1, being continuous on the entire surface) proved to be effective in minimizing wetting, with the moisture uptake maintained just slightly above 2 kg/m². The self-adhered vapour-permeable membrane kept the MC readings from inside the CLT around 15% and that of the plywood spline around 20%. The 5% MC reading difference between the CLT and plywood was attributed to the effect of the plywood adhesive on meter readings (Wang and Thomas 2018). Comparing water repellents to membranes as potential moisture protective measures for CLT, it is challenging for a coating to bridge gaps at joints between panels and between boards in a CLT panel or to seal all wood surfaces exposed at joints. Moreover, although the cost of water repellants is typically lower compared to the cost of membranes, it is labour-intensive to apply water repellent at each joint so that it adequately protects the exposed edges of CLT, the face and edges of the spline, and around the multiple holes. By comparison, it should be relatively straightforward to install a membrane on the surface of an installed floor or a roof (with joints) at the site. Detailing should be provided for the service openings, holes, and gaps in the floors to prevent trapping moisture. When the membrane is pre-installed in the factory, membrane strips should be quickly overlaid over joints, once the panels are connected.
Figure 17  Surface moisture uptake of CLT (Group 2) with or without a butt joint, with or without surface treatment during three months’ outdoor exposure.

Figure 18  Measured moisture content from the plywood spline of a butt joint of CLT (Group 2), with or without surface treatment during three months’ outdoor exposure.
7.2.3 Exposure of CLT Edge to Weather

The edges of CLT, when exposed are known to be more vulnerable to moisture penetration than wide surfaces due to faster movement of moisture in the longitudinal direction. The test of Group 3 specimens showed that water penetrated much faster and more deeply through an untreated edge (end grain), compared to transverse penetration (Figure 20); the moisture uptake of the vertically exposed CLT specimen reached 40 kg/m² after three months’ exposure (Figure 21). This confirmed that it should be a higher priority to protect CLT edges over wide surfaces, just like other wood products. The three water repellents applied on the edges showed different levels of effectiveness in preventing water absorption and penetration (Figure 21; Figure 22; Figure 23). TWS and WR No. 6 turned out to be similar and reduced the surface moisture uptake by about 30%. WR No. 7, an end grain sealer recommended by the manufacturer for protecting end grain of wood products and reducing checking, was found to be the most effective. It kept the moisture uptake amount to within 5 kg/m² over the three months’ exposure, making the absorption of a coated edge similar to that of an untreated wide surface (Figure 21). It also kept the measured MCs at the depth of 25 mm below 15% (Figure 23); however, the MCs at a depth of 12 mm reached 25% after about two months’ exposure (Figure 22). The test indicated that for CLT panels installed horizontally, pre-applying an end grain sealer such as WR No. 7 on the vertical edges (including the exposed edges of pre-drilled holes) of CLT panels in factory would provide good protection during construction under most climatic/construction conditions. It was expected that the edges of CLT panels can be brushed with a water repellent relatively easily in the factory. For extremely severe environment,
including edges oriented horizontally, it is expected that a self-adhered vapour-permeable membrane would be better to prevent water penetration from end grain, while maintaining the drying capacity.

Figure 20  Measured moisture content at two depths in the longitudinal direction from an exposed CLT edge (Group 3) during three months’ outdoor exposure

Figure 21  Surface moisture uptake from an exposed CLT edge (Group 3), with or without edge treatment with water repellent during three months’ outdoor exposure
Figure 22  Measured moisture content at 12 mm deep in the longitudinal direction from an exposed CLT edge (Group 3), with or without edge treatment with water repellent during three months' outdoor exposure

Figure 23  Measured moisture content at 25 mm deep in the longitudinal direction from an exposed CLT edge (Group 3), with or without edge treatment during three months' outdoor exposure
7.3 Impact of Wet Concrete Topping

When wet concrete was poured to a thickness of 40 mm on a dry CLT surface (i.e., without initial wetting) in the test of Group 4 specimens, the MC readings from the surface (i.e., 6 mm deep) increased only slightly and then stayed at about 15% for the duration of the test (Figure 24); no change in MC was detected at the depth of 12 mm (Figure 25). This is consistent with observations on the time required for moisture to penetrate side grain versus the time required for the concrete to initially set or harden (about 12 hours). The pre-wetted CLT specimen (CLT No. 13), which was exposed to weather for about one month and reached a MC of about 21% in the top (6 mm deep) and 18% at 12 mm deep after the initial wetting, appeared to be able to dry at both measurement locations. It is known that curing of concrete is primarily a hydration reaction. But the drying was slow and the MC at 6 mm deep remained at about 18% two months after installation of the concrete topping. In theory, mould may grow in the wood surface if other conditions, such as temperature, oxygen levels, and pH\(^9\) are favourable. The dry OSB specimens responded in a way similar to the dry CLT specimen, with the measured MCs largely staying below 20% following installation of the concrete topping (Figure 26). The more absorptive plywood showed clearer response to the pouring of wet concrete, signified by the increasing MC in the top surface; this was also followed by drying (Figure 27). Note the MC readings from the plywood specimens were believed to be overestimated due to the effect of the adhesive used to make plywood\(^10\) (Wang and Thomas 2018). It is known that thin panels, such as plywood and OSB are able to dry faster than thick CLT, when conditions allow (Wang 2014). The two types of membranes tested showed appreciable effect in reducing moisture interaction between the wood and the wet concrete above. However, this study indicated that the overall need for protecting wood surface against moisture from wet concrete topping was not large under the test conditions in this study. The most practical protection is probably to keep the wood reasonably dry (e.g., with a MC below 16%) by sheltering it and avoiding other water sources, such as rain before and after installing concrete topping. If the surface of mass timber is too wet, measures, such as space heating can be provided to accelerate drying prior to pouring concrete topping. Note some concrete topping products may have a higher water ratio and may consequently introduce more moisture into the wood below.

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\(^9\) Concrete might slightly increase the alkalinity of wood and reduce the risk of mould growth.

\(^10\) The overestimation is higher at a higher MC.
Figure 24  Measured moisture content at 6 mm deep below CLT surface (Group 4) with wet concrete topping installed on the surface

Figure 25  Measured moisture content at 12 mm deep below CLT surface (Group 4) with wet concrete topping installed on the surface
Figure 26  Measured moisture content in top surface and at mid-depth of OSB (Group 4) with wet concrete topping installed on the surface

Figure 27  Measured moisture content in top surface and at mid-depth of plywood (Group 4) with wet concrete topping installed on the surface
7.4 Impact of Rising Moisture from Damp Concrete

Wood members in direct contact with concrete or masonry may be susceptible to penetration of rising moisture since porous materials such as concrete can transport moisture from ground. During construction a concrete slab also often has standing water, which can reach adjacent wood members. Because of this, sill plates are required to be pressure-treated with a preservative to resist decay if the vertical clearance to the finished ground level is less than 150 mm and a damp-proof membrane is not used to separate the wood from the concrete (NRC 2015). Similarly concerns about rising moisture exist when CLT is in contact with concrete, for example, when a CLT wall bears on a concrete foundation or slab. Under such conditions, the CLT should first be installed above a curb to prevent standing water from reaching the CLT panel. To protect the CLT from water transported through the concrete, a preservative-treated sill plate may be installed below untreated CLT, and the CLT can have treated lamina or localized preservative treatment under conditions with a severe decay hazard (Gagnon and Pirvu 2011; Karacabeyli and Douglas 2013).

The purpose of the test using Group 5 specimens was to assess the amount of rising moisture from damp concrete, which was created in this study to simulate a severe wetting scenario and to consequently identify solutions by testing two water repellents (see the test setup in Figure 3). In this case, the concrete is not intended to be in contact with water when in service; but it may accumulate standing water near where the CLT panel contacts the concrete and water may therefore find its way to the CLT-concrete interface. Such moisture diffusion is typically considered to be a slow process. However, this test showed that an untreated edge of the CLT control specimen picked up moisture of about 4.3 kg/m² from the damp concrete block below over three months’ exposure (Figure 28). This level of moisture uptake was actually higher than that through an untreated wide surface when the CLT was horizontally exposed to weather for three months, and was similar to that through a CLT edge treated with an end grain sealer when the edge was exposed to weather for three months. The measured MCs at two depths from the untreated CLT edge stayed below 20% during three months’ exposure (Figure 29). The two water repellents tested did not reduce the surface moisture uptake (the slight increases in the moisture uptake of the treated specimens compared to the untreated specimens is inconsistent with the MC readings and may be considered as a test error). WR No. 7, i.e., the end grain sealer tested in this study appeared to perform better than TVS and kept the MCs measured inside the CLT largely below 15% in the duration of three months. This reduced level of moisture penetration should be tolerated by the inherent water storage capacity of wood. Overall, the study suggested that damp-proof treatment should be applied to the edges of CLT (or other wood products) in direct contact with a concrete slab (or foundation). It appears adequate to treat the edge with a good water repellent, such as the end grain sealer tested in order to slow down moisture diffusion to a level that can be tolerated by the CLT panel. Installing a damp-proof membrane, such as the self-adhered membranes tested in this study should be a more robust practice, if such a need arises.
Figure 28 Surface moisture uptake from a CLT edge (Group 5) sitting on a damp concrete block under sheltered conditions

Figure 29 Measured moisture content at 12 mm and 25 mm deep into end grain of CLT (Group 5) with edge sitting on a damp concrete block under sheltered conditions
7.5 Impact of Fire Safety Measures on Drying

A fire safety plan may require certain fire risk reduction measures be taken during the construction. In the case of a large mass timber construction project, this may include installing drywall as early as possible (e.g., when there is sufficient protection from the weather). Although such measures may reduce the construction fire risk, there are concerns among practitioners about the loss of drying capacity, for example, when a fire-rated covering (e.g. gypsum wallboard, mineral wool insulation, coating etc.) is installed over wet wood, or the wood gets wet after the drywall or other surface covering materials are installed.

The test of Group 6 specimens was designed to assess the drying rates when CLT wetted through outdoor exposure for about one month was covered with drywall (one layer or three layers), or rigid mineral wool insulation (38 mm thick) (see the test setup in Figure 4). There was no further wetting during the drying test. The drying rate was calculated based on the ratio between the amount of moisture (by weight) dissipated during the drying phase in the shed and the amount of moisture picked up during the initial outdoor exposure, expressed in percentage. It was found that the mineral wool insulation, known to be highly vapour permeable almost had no negative effect on the drying rates of the wetted CLT (Figure 30; Table 2). However, one layer of drywall reduced the drying rates by about 20%, and three layers of drywall reduced the drying rates by about 50%. The MC measurements at the two depths below showed negligible effects from installing the drywall, with the measured MCs largely remaining below 20% (Figure 31; Figure 32). The test showed that only 40% of the moisture gained during the initial outdoor wetting process (for one month) evaporated from the uncovered CLT over two months of drying under open shed conditions (Figure 30). This indicates that CLT dries slowly under damp exterior conditions. Although using mineral wool or drywall as a fire safety measure will allow the wood to dry; the slow drying under unfavourable environmental conditions (cold and damp) will cause the wood to stay damp for a duration that can be sufficient to lead to mould growth. It is therefore safest to keep the wood dry, or to dry wetted wood before covering it with other materials (e.g., drywall, membranes etc.). Once the building is enclosed, lowering the humidity in the environment through use of space heating or dehumidifiers is expected to greatly speed up drying.
Figure 30  Effect of a fire-proof covering on drying rates of CLT of Group 6

Figure 31  Measured moisture content at 6 mm below CLT surface (Group 6) covered with a fire-proof material
8 CONCLUSIONS

1. This study confirmed that water was generally slow to penetrate into the wide surface of CLT (i.e., in transverse direction of wood); by comparison, exposed end grain on CLT edges are much more susceptible to moisture absorption and penetration and therefore deserve more attention for moisture protection. Once wetted to the extent that water has penetrated deeply, CLT in a damp and cold environment will be slow to dry.

2. When a horizontal wide surface of CLT (without joint) was exposed to intense rain for three months in the winter in Vancouver, none of the six water repellents tested was found to effectively reduce water absorption or penetration. A lumber wrap tested was slightly better than the water repellants. The two self-adhered membranes including a vapour impermeable and a vapour-permeable product assessed were the most effective to prevent wetting.

3. When a horizontal surface of CLT with a butt joint covered with plywood spline was exposed to intense rain for three months, the joint trapped and absorbed moisture not only in the absorptive plywood, but also in the CLT through the exposed end grain. The continuous self-adhered vapour permeable membrane tested proved to be effective to protect such joints when it was applied over the joint.

4. When the edge of CLT was directly exposed to intense rain for three months, the end grain sealer tested in this study was found to be the most effective among the three water repellents.
repellents assessed to reduce moisture uptake and penetration. The self-adhered vapour permeable membrane tested in this study is expected to provide better protection not only by preventing the initial wetting, but also by maintaining the drying capacity in the event moisture does find its way behind the membrane.

5. Moisture in the wet light-weight concrete topping (a product of self-leveling floor screed) assessed in this study did not cause considerable wetting in the CLT below.

6. When an untreated edge of CLT sat on damp concrete for three months, the rising moisture caused considerable wetting. The two water repellents tested did not reduce surface moisture uptake; however, the end grain sealer tested kept the MC at two measurements locations largely below 15%.

7. Regarding the impact of a fire-proof covering on the drying performance of CLT, 25 mm thick mineral wool insulation had negligible impact on drying capacity, one layer of drywall (12 mm thick) reduced the drying rates by about 20%, and three layers of drywall reduced the drying rates by about 50%. But the slow drying of CLT in damp environment would require the wood be kept dry before and after installing any covering material.

9 RECOMMENDATIONS ON PROTECTION PRACTICES

The following table summarizes the implications of this study to on-site moisture protection of CLT. More detailed guidelines on construction moisture management for CLT buildings can be found in the updated CLT Handbook (Canadian edition) to be published later this year (FPIinnovations 2018).

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Priority of moisture protection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shipping</td>
<td>CLT should be covered to prevent rain wetting; although effective, panels covered with lumber wrap should not be exposed to rain for too long (e.g., more than 20 days). Avoid orienting end grain surfaces to rain.</td>
</tr>
<tr>
<td>Short-term storage</td>
<td>CLT should be stored above ground and sheltered to prevent wetting for a duration that would allow water to penetrate. Avoid storing CLT with end grain surfaces exposed to rain and splash back. Panels covered with lumber wrap should not be exposed to rain for long (i.e., more than 20 days). Where a sheltered space cannot be provided, additional layer of protection should be arranged and sloped to avoid ponding of water.</td>
</tr>
<tr>
<td>Scenario</td>
<td>Priority of moisture protection</td>
</tr>
<tr>
<td>----------------------------------------------</td>
<td>-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Long-term storage</td>
<td>Follow the minimum recommendations for short-term storage. Wood adsorbs moisture from high humidity environments. Storage under damp environmental conditions should be minimized to prevent wetting caused by high humidity.</td>
</tr>
<tr>
<td>CLT floor without wet concrete topping during construction</td>
<td>Minimize the time of rain wetting by sheltering the floor, such as with sealed upper floors or a roof as early as possible. Clear floors of any standing water. Edges including those exposed by holes, notches, and joints should be pre-sealed with a good end grain sealer to reduce water absorption resulting from dripping through joints and gaps. Under severe conditions, pre-install or site-install a self-adhered vapour-permeable membrane to effectively protect all joints and to minimize moisture trapping. All joints/gaps/holes should be immediately sealed during installation to prevent water ingress.</td>
</tr>
<tr>
<td>CLT floor to be installed with wet concrete topping during construction</td>
<td>Minimize the time of rain wetting by sheltering the floor, such as with sealed upper floors or a roof as early as possible. Ideally the roof should be installed before pouring concrete topping on floors. Clear floors of any standing water. Provide rain protection before and after installing wet concrete topping. Specify a concrete topping product with a low water ratio, when possible. Where the CLT has been exposed to wetting and the moisture content below the surface is confirmed to be high, forced drying measures, such as space heating may be used to accelerate drying prior to pouring concrete topping. Under severe conditions, pre-install or site-install a self-adhered vapour-permeable membrane to effectively protect all joints and to minimize moisture trapping. All joints/gaps/holes should be immediately sealed during installation to prevent water ingress.</td>
</tr>
<tr>
<td>CLT roof</td>
<td>Pre-install a self-adhered permeable membrane as temporary roofing, or a self-adhered impermeable membrane, which will become part of the final roofing. All joints/gaps should be immediately sealed on-site with strips of the self-adhered permeable membrane to prevent water ingress once the panels are connected.</td>
</tr>
<tr>
<td>CLT wall on concrete slab</td>
<td>Pre-installing a good water repellent can slow down moisture diffusion and keep the moisture load within an acceptable range. Pre-installing a damp-proof membrane, such as the vapour impermeable...</td>
</tr>
</tbody>
</table>
### Scenario | Priority of moisture protection
--- | ---
CLT to be covered with a fire-safety measure | self-adhered membranes tested in this study is a preferred solution.

Minimize the time of wetting by sheltering the CLT as early as possible. The wood dries slowly, under damp conditions in particular once severe wetting occurs.

Mineral wool insulation is expected to have better drying performance than drywall due to its higher vapour permeability.

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**10 REFERENCES**


APPENDIX I  WEATHER CONDITIONS DURING TEST

Figure 33  Hourly temperature and relative humidity measured at the test site using a weather station from October 24 2017 to January 2018

Figure 34  Hourly precipitation measured at the test site using a weather station from October 24 2017 to January 2018
Figure 35  Hourly temperature and relative humidity measured in the shed from October 24 2017 to January 2018
APPENDIX II EXTRA CHARTS OF TEST RESULTS

Figure 36  Moisture uptake of CLT (Group 1) with surface treated with water repellent during three months’ exposure to weather

Figure 37  Measured MC at 6 mm deep below surface of CLT (Group 1) with surface treated with water repellent during three months’ exposure to weather
Figure 38 Measured MC at 12 mm deep below surface of CLT (Group 1) with surface treated with water repellent during three months’ exposure to weather

Figure 39 Measured MC in the top surface of CLT, plywood, OSB, and nail-laminated timber covered with plywood (Group 1) during three months’ exposure to weather
Figure 40  Measured MC at 12 mm in CLT, and mid-depth of plywood, OSB, and nail-laminated timber covered with plywood (Group 1) during three months’ exposure to weather

Figure 41  Moisture uptake of plywood (Group 1) with or without surface treatment during three months’ exposure to weather
Figure 42  Measured MC in surface of plywood (Group 1) with or without surface treatment during three months’ exposure to weather

Figure 43  Measured MC at mid-depth of plywood (Group 1) with or without surface treatment during three months’ exposure to weather
Figure 44  Moisture uptake of OSB (Group 1) with or without surface treatment during three months' exposure to weather

Figure 45  Measured MC in surface of OSB (Group 1) with or without surface treatment during three months’ exposure to weather
Figure 46  Measured MC at mid-depth of OSB (Group 1) with or without surface treatment during three months’ exposure to weather
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Figure 47  A CLT specimen with plywood spline covering a butt joint being prepared

Figure 48  A CLT specimen with the top wide surface being treated with a water repellent
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Figure 50  A method designed to install moisture pin sensors at given depths consistently
Figure 51  A method designed to install moisture pin sensors at given depths consistently

Figure 52  A method designed to install moisture pin sensors at given depths consistently
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Figure 55  Specimens installed with a type of protective membrane

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