Effect of Exterior Wood Coatings on the Durability of Cross-laminated Timber against Mold and Decay Fungi

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Cross-laminated timber (CLT) is increasingly used in building construction worldwide. Durability of CLT against fungal attack has yet to be fully explored. Water intrusion in mass timber can yield dimensional changes and microbial growth. This study evaluated the performance of CLT coated with various water- and solvent-based stains commercially available in the United States. Twelve coatings were tested for moisture excluding effectiveness, water repellency effectiveness, volumetric swelling, and anti-swelling efficiency. Only five coatings repelled water, limiting dimensional changes. A modified version of AWPA E10-16 (2016) was performed to evaluate decay of the coated CLT samples. Weight losses were recorded after 18 weeks' exposure to the brown-rot decay fungus *Gloeophyllum trabeum*. In accelerated mold testing, coated CLT samples were grown in chambers containing spores of *Aspergillus* sp., *Rhizopus* sp., and *Penicillium* sp. for 29 d and assessed visually for mold growth. In both tests, coating C (transparent, water-based, alkyd/acrylic resin) performed the best among the tested coatings. Mold growth was completely prevented, and weight loss caused by *G. trabeum* was approximately 1.33%. Although coating C prevented decay for 18 weeks, coatings are not intended to protect against decay fungi. However, they may offer short-term protection during transport, storage, and construction.

Keywords: Surface treatment; Coatings; Mass-timber; Cross laminated timber deterioration; Mold

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INTRODUCTION

The use of mass timber in building construction has increased dramatically over the last decade (Harte 2017). Cross-laminated timber (CLT) panels present numerous advantages compared to construction materials traditionally used for mid- and high-rise structures, such as masonry, concrete, and steel (Smith *et al*. 2018). Safe and reliable progress of these products necessitates development and adoption of techniques to extend their durability. Cross-laminated timber is usually made of softwood lumber that is considered non-durable (Clausen 2010). As the use of mass timber increases throughout North America, protective methods are critical to extending their service life, especially in regions with accentuated hazards, such as termites and fungal degradation. Although they are not designed to be used in ground contact, careful precautions are needed to minimize the risk of decay and other economic losses.

Among many factors that may contribute to deterioration of building materials, water is one of the most detrimental in mass timber products. Moisture control is essential to the proper functioning of any building (Trechsel 2002). Wang *et al*. (2018) noted that any material can experience some type of moisture issue, which might be caused by vapor condensation, roof leaks, failures at building envelope protection, or wicking from wet foundation. Moisture exposure can occur due to numerous reasons, such as excessive wetting during or after construction (Bora *et al*. 2019). The material configuration inherent in CLT design contributes to water absorption throughout the panel. The high absorption capability of wood grain may result in warping of the CLT laminas, caused by moisture differences in the layers. Shrinkage and swelling are likely to cause separation from the adhesive layer of the CLT. According to Carll and Wiedenhoeft (2009), the integrity and strength of bonded wood and progressive deflection of wood composites can be impaired by swelling-induced stresses caused by moisture and by repeated cycles of drying and wetting. Even mechanical connections may be compromised by moisture exposure.

Dimensional changes, moisture damage, and microbial growth can eventually occur with short-term wetting or high relative humidity (RH) (80% to 95%) (Schmidt and Riggio 2019). Cappelazzi *et al*. (2020) noted that in North America, moisture control during construction is minimal, independently of the material used. Water intrusion in CLT is generally proportional to the volume of wood present. Thus, panel thickness influences the rate of moisture uptake. Cross-laminated timber flooring exposed to rainfall in Oregon, USA, absorbed from 12% to 27%, close to a point where fungal growth begins (Morrell *et al*. 2018).

Moistened materials are more likely to experience fungal growth. Mold is a persistent issue due its possible occurrence at any manufacturing stage of wood products or when the product is in use if it is wet enough (Clausen 2010). Molds are likely to occur on coated wood surfaces in either indoor or outdoor conditions. Although mold fungi do not affect the strength of wood materials, they are considered a major maintenance concern and are usually associated with respiratory issues in building occupants (Bornehag *et al*. 2001; Purokivi *et al*. 2001). Conversely, decay fungi (except for dry rot fungi) are more likely to attack wood materials when free water is available, which is normally at approximately 30% moisture content (MC). When the MC increases to 60% to 80%, the decay rate increases (Stienen *et al*. 2014; Brischke *et al*. 2017,). As decay progresses, significant deterioration of the wood is seen to a point where the mechanical and physical properties are completely compromised.

There are several protection methods designed to protect timber products against microbiological deterioration; the most common is the use of pressure-treated wood. However, because mass timber dimensions are incompatible with currently available pressure-treatment cylinders, pressure treatment of the finished product is not suitable (Cappelazzi *et al*. 2020). Consequently, surface coatings have become popular as a potential solution for extending mass timber service life because of both the water repellent and anti-fungal chemicals found within some coatings (Rosu *et al*. 2018, 2020).

Currently, there is no available study on the performance of exterior wood coatings on mass timber exposed to water, mold, and decay fungi. To address this issue, coated and uncoated CLT samples were tested in this work based on their water properties and their ability to control mold growth. Based on the progression of decay on control samples, a modified soil block test was developed to investigate the ability of coatings to prevent fungal degradation.

EXPERIMENTAL

Materials and Methods

Moisture properties

To determine water repellency effectiveness (WRE) and anti-swelling efficiency (ASE), two CLT panels were manufactured using a Dieffenbacher laboratory hydraulic press. Six No. #2 2 in × 4 in Southern yellow pine (*Pinus* spp.) lumber pieces were planed (within 12 h), trimmed, and cut at two different lengths: 762 mm (outer layer) and 305 mm (core layer). The layers were glued together (glue-spread rate of 147 g/m^2) with polyurethane resin (PUR) and cold pressed (23 °C) for 3 h at 738 kPa.

The criteria for using Southern yellow pine CLT for this experiment was based on two factors. First, to perform a reliable and precise moisture properties evaluation is critical to have uniform and free of defects material. Second, in the local market, Southern yellow pine boards are easily found. Furthermore, the exterior wood coatings could be applied to manufactured panels and compared with less variation due to substrate.

Seventy-eight samples (free of knots, resin pockets, cracks, and end joints) measuring 110 mm × 50 mm × 25 mm (length × width × height) were selected for testing based on absence of defects, similarity in size, direction of growth rings, and wood density. The samples were randomized and distributed to each treatment. The treatments comprised 12 US commercially available water- and solvent-based coatings/stains: transparent, semitransparent, and white paint. The specimens were coated according to manufacturer instructions, and a set of samples was left uncoated (Table 1).

Table 1. Description of Selected Coatings System

Coating	Base	Type	Color	Resin Type	Replicates
A (Alk/Acr, W[1])	Water	Transparent	Natural	Alkyd/Acrylic	6
B (Acr, W[1])	Water	Transparent	Natural	Acrylic	6
C (Alk/Acr, W[1])	Water	Transparent	Clear	Alkyd/Acrylic	6
D (Alk, S[2])	Solvent	Transparent	Natural	Alkyd	6
E (Alk, S[2])	Solvent	Transparent	Natural	Alkyd	6
F (Acr, W[1])	Water	Semitransparent	Deep gold	Acrylic	6
G (Acr, W[1])	Water	Semitransparent	Cedar	Acrylic	6
H (Alk/Acr, W[1])	Water	Semitransparent	Cedar	Alkyd/Acrylic	6
I (Alk, S[2])	Solvent	Semitransparent	Redwood	Alkyd	6
J (Alk, S[2])	Solvent	Semitransparent	Cedar	Alkyd	6
K (Acr, W[1])	Water	Paint	White	Acrylic	6
L (Alk/Acr, W[1])	Water	Paint	White	Alkyd/Acrylic	6
Control	N/A	N/A	N/A	N/A	6

W[1] – water based; S[2] – solvent based; Alk – alkyd; Acr – acrylic

After being treated, the samples were air dried for 3 d at room temperature, weighed, and conditioned in an environmental chamber at 66% RH and 24 °C (12% equilibrium moisture content) until the samples reached a consistent weight. Then, the moisture excluding effectiveness (MEE) was calculated as follows (Eq. 1), based on Feist *et al*. (1985),

$$MEE(\%) = \frac{M_{\mathrm{U}} - M_{\mathrm{T}}}{M_{\mathrm{U}}} \times 100 \tag{1}$$

where M_U is the equilibrium moisture content of the untreated samples, and M_T is the equilibrium moisture content of the treated samples.

To determine the water uptake capacity, after being conditioned at 66% RH and 24 °C and weighed, the samples were submerged into a water bath and weighed at the following intervals: 30 min, 1 h, 2 h, 24 h, 48 h, and 72 h. The WRE was determined using Eq. 2,

$$WRE(\%) = \frac{W_U - W_T}{W_U} \times 100 \quad (2)$$

where W_U is the water uptake of the untreated samples, and W_T is the water uptake of the treated samples.

Dimensional changes due to moisture uptake were determined by measuring the volume after periods of 24 h, 48 h, and 72 h. The volumes of the CLT pieces were obtained by the caliper method (measurement at the same spots for height, width, and thickness for error reduction), and the volumetric swelling coefficient (*S*) was calculated from Eq. 3,

$$S(\%) = \frac{V_2 - V_1}{V_1} \quad (3)$$

where V_2 is the wood volume after humidity conditioning or wetting with water, and V_1 is the wood volume of the air-dried sample before conditioning or wetting.

Anti-swelling efficiency was calculated for each time period (24 h, 48 h, and 72 h) based on the volumetric swelling (Eq. 4),

$$ASE(\%) = \frac{S_2 - S_1}{S_1} \quad (4)$$

where S_2 is the treated volumetric swelling coefficient, and S_1 is the untreated volumetric swelling coefficient.

Accelerated mold growth

A mold growth test was performed on samples generated from the three-ply southern yellow pine panel described earlier to determine the ability of the coatings to inhibit mold growth.

Table 2. Specifications of Tested Coating Systems

Treatment	Coating or Surface Description	Resin Type	No. of coats
A (Alk/Acr, W[1])	W[1], transparent penetrating wood finish	Alkyd/Acrylic	2
C (Alk/Acr, W[1])	W[1], transparent, UV resistant	Alkyd/Acrylic	3
F (Acr, W[1])	W[1], semitransparent, water and UV resistant	Acrylic	2
I (Alk, S[2])	S[2], transparent, mildew and water resistant	Alkyd	2
J (Alk, S[2])	S[2], semitransparent, water repellent	Alkyd	1
Control	Uncoated sample	None	None

Number of coats applied was determined by manufacturer recommendations. W[1] – water based; S[2] – solvent based; Alk – alkyd; Acr – acrylic

Based on the MEE, WRE, and ASE, 30 samples: five per coating treatment were selected to be tested against mold growth. The samples were randomized and distributed to each treatment according to dry weight to minimize sources of variation. The treatments consisted of five US commercially available water- and solvent-based coatings/stains. The coating types were transparent and semitransparent (Table 2). The specimens were coated according to manufacturer instructions, with some control samples left uncoated.

The accelerated mold growth test was performed at the Department of Forestry and Wood Technology, Linnaeus University (Växjö, Sweden). The test was conducted in a climate chamber (Memmert HCP 246, Memmert GmbH, Schwabach, Germany) under non-sterile conditions. Temperature and RH in the chamber were monitored throughout the experimental period. Samples of pine sapwood naturally infected by *Aspergillus* sp., *Rhizopus* sp., and *Penicillium* sp. were used as inocula sources. Over a period of 14 d, the chamber was kept at temperature less than 27 °C and 95% RH to be infested with spores. Afterwards, the test samples were hung edgewise from the top through aluminum bars spaced to allow a minimum 10-mm gap between two samples (Fig. 1).

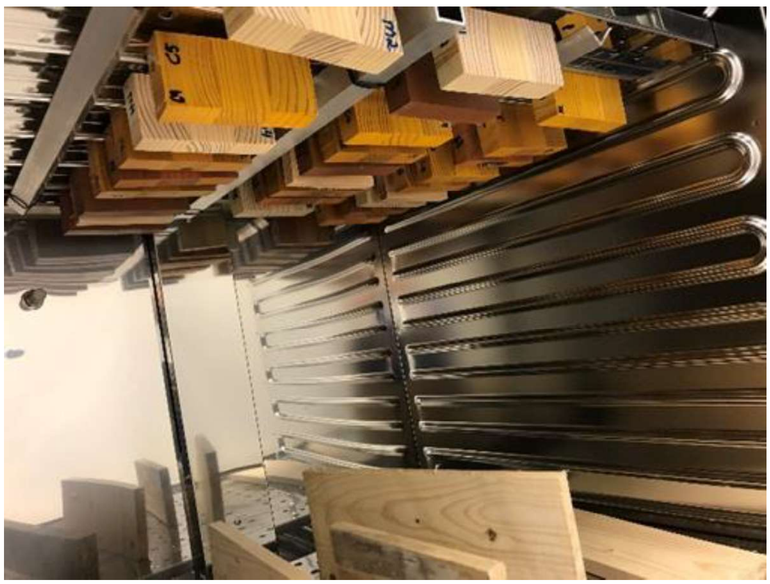

Fig. 1. Accelerated mold test setup

After 29 d of incubation, as abundant mold growth was observed on some sample surfaces, three edges and two flat sides of each sample were evaluated for mold growth (Table 3). The degree of mold growth was visually rated from 0 to 5.

Table 3. Description of Mold Grades by Sehlstedt-Persson *et al*. (2011)

Mold Grade	Description
0	No visible mold growth
1	Small amount of mold growth: some doubt about mold
2	Sparse mold growth without doubt
3	Moderate mold growth: most of the surface not covered with mold
4	Heavy mold growth: surface entirely covered with fluffy mycelia and spores
5	Very heavy mold growth: multi-colored mold in addition with black mold

The grading system in this method does not ensure any specific period of time for a mold-free surface. It does show the potential of a coating to prevent mold development during the 29 d of exposure in the set conditions (95% RH and 27 °C).

Decay test

Test samples were prepared from three-ply (three layers) CLT panels (SmartLam LLC, Whitefish, MT, USA) manufactured with hemlock-fir (hem-fir) (*Tsuga canadensis*, *Abies* spp.) panels. This test used hem-fir samples because of their availability in the North American market. A preliminary test set was designed to determine fungal decay progression in uncoated CLT in an accelerated laboratory test. The fungal soil block assay AWPA E10-16 (2016) is a standardized method based on wood blocks of either 14 mm × 14 mm × 14 mm or 19 mm × 19 mm × 19 mm. For the standard AWPA E10-16 (2016) soil block test, specimens are deliberately subjected to decay for either 12 weeks or 24 weeks to achieve 40% weight loss based on fungal species and specimen size. The large CLT samples used here required a lower baseline (30%) because of the period of exposure and the specimens' volume. The samples matched the dimensions described earlier in section 2.1 and were arranged in duplicate for each exposure time (8 weeks, 12 weeks, 18 weeks, and 24 weeks) to determine the baseline. The test was conducted following the AWPA E10-16 (2016) protocol with some modifications to ensure the feasibility of the test with the CLT pieces as follows:

Three 2-L acrylic containers were filled with 700 g of soil and 300 mL of water based on water-holding-capacity testing. Two feeder strips measuring 72 mm × 20 mm × 3 mm (length × width × height) were added to each set (container + soil + water). The containers were later autoclaved at 20.7 kPa and 150 °C with aluminum foil on top for 45 min while their lids were sterilized with ethanol (70%).

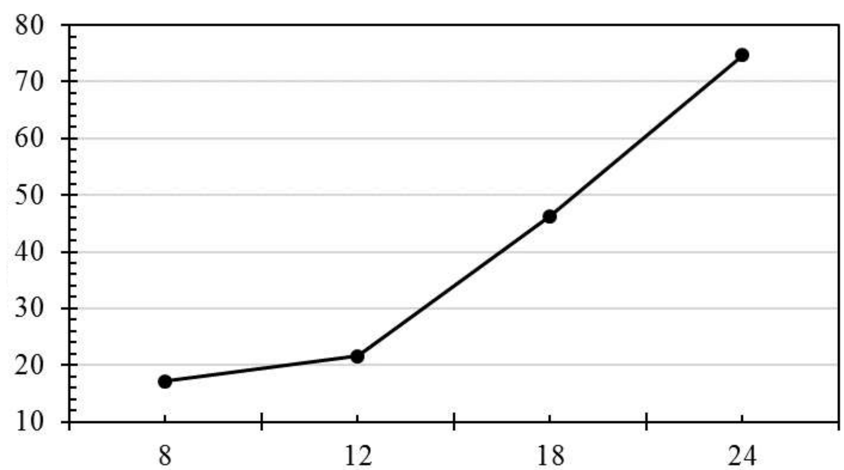

Fig. 2. Weight loss progression of control CLT specimens during 24 weeks of soil block test for baseline determination

Mycelial plugs of *Gloeophyllum trabeum* (Pers. ex Fr.) Murr. isolate MAD 617 (USDA-NRS-FMHC, Forest Products Laboratory, Madison, WI, USA) were inoculated in each container and were left to grow until full colonization of the feeder strips (4 weeks). Thereafter, two CLT samples were introduced to each container. The test was conducted in an incubator at 24 °C for 24 weeks. At the ends of 8 weeks, 12 weeks, 18 weeks, and 24 weeks, the samples were removed from testing, and their weight losses were recorded. Figure 2 shows the weight loss progression throughout the test.

Preliminary testing indicated sufficient weight loss (weight loss of approximately 40%) after 18 weeks of exposure, which determined the period for the main exposure. Thirty-six samples of CLT were prepared: 30 coated and 6 uncoated. The test followed the same procedures mentioned earlier in this section. The samples were later examined according to visual evidence of decay and weight loss (%).

Statistical analyses

Mold grades on different samples were analyzed using the statistical software package IBM SPSS Statistics, version 23 (IBM Corporation, Armonk, NY, USA). One-way analysis of variance (ANOVA) was applied to determine whether mold grades were significantly different among the sample categories. A 5% level of significance was used to detect differences, and when a significant difference was found, Duncan's multiple range test was performed.

Analyses of variance were performed in the other response variables (MEE, WRE, ASE, and weight loss by *G. trabeum*) using Statistical Analysis System (SAS) software, version 9.4 (SAS Institute, Cary, NC, USA). The MEE and weight loss by *G. trabeum* were analyzed under completely randomized design based on coating effect. The WRE and ASE were examined based on two factors: coating type and soaking time. When the interaction between factors was not significant, each factor was analyzed in isolation.

RESULTS AND DISCUSSION

Moisture Properties

The MEE of coating I was substantially greater than those of the other coatings, *i.e.*, coating I was more hydrophobic, which prevented moisture uptake on the coating surface (Table 4).

Table 4. Moisture-related Properties of Coated CLT at 66% RH and 24 °C

Coating	MEE (%)	WRE (%)	ASE (%)
A. Alk/Acr (W)	12.9^{G}	57.5^{DE}	20.5^{BC}
B. Acr (W)	23.3^{CDE}	52.3^{EF}	10.5^{CD}
C. Alk/Acr (W)	21.0^{DE}	92.0^{A}	56.7^{A}
D. Alk (S)	26.8^{C}	44.8^{F}	11.4^{CD}
E. Alk (S)	26.6^{C}	57.5^{DE}	12.6^{C}
F. Acr (W)	26.8^{C}	68.2^{C}	22.1^{BC}
G. Acr(W)	15.0^{FG}	-9.3^{H}	-10.5^{E}
H. Alk/Acr (W)	25.6^{CD}	7.8^{G}	-9.7^{E}
I. Alk (S)	88.5^{A}	81.5^{B}	28.0^{BC}
J. Alk (S)	0.30^{H}	78.6^{B}	34.4^{B}
K. Acr(W)	34.9^{B}	64.3^{C}	-7.5^{DE}
L. Acr(W)	19.1^{EF}	81.1^{B}	17.1^{BC}

Results followed by the same letter per column and coating are not significantly different by the t-test (Least Square Difference, LSD) at α = 0.05. The average WRE and ASE values are given for a 72-h soak. W – water-based system; S – solvent-based system; Alk – alkyd; Acr – acrylic

This characteristic is important in places where coated wood is not directly exposed to water but is in contact with high RH. In that case, coating I would likely promote moisture protection in damp buildings. In fact, Schmidt and Riggio (2019) noted that moisture management is crucial in the serviceability and preservation of buildings.

The interaction between time and treatment for WRE was statistically significant at the 5% level by the t-test ($p < 0.05$) for short time exposure (Fig. 3). As the test progressed, soaking times and WRE slightly decreased in the first few hours except in coatings G and H (water uptake greater than untreated samples). Water repellency measures a coating's ability to decrease water absorption. Moisture exclusion is based on retarding the transmission of water vapor (Williams 1999).

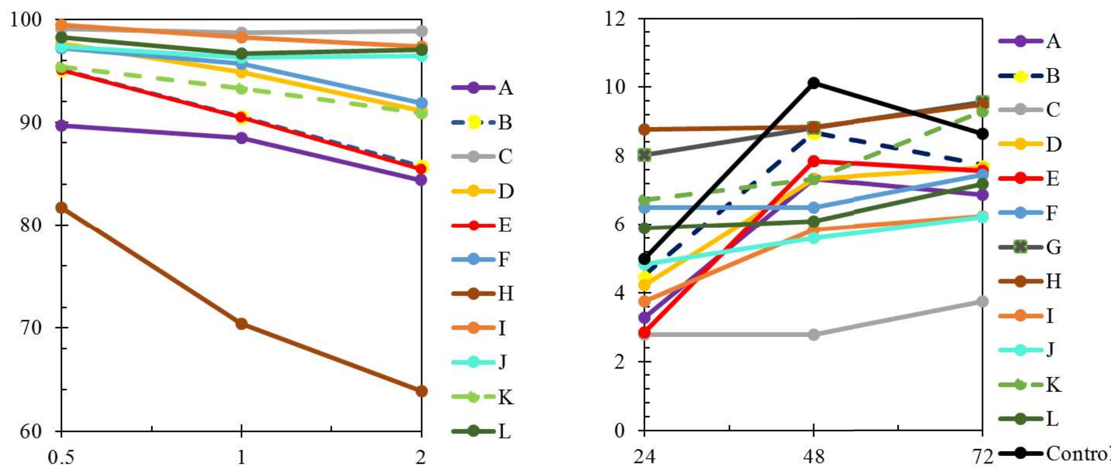

Fig. 3. Water repellency during 2 h of water soaking and volumetric swelling during 72 h of water soaking. Coating G was not included on WRE graph. At 0.5, 1, and 2 h of water bath the WRE were 3, -24, -22, respectively.

The WRE test showed that at least seven coatings were efficient in preventing more than 90% of water intrusion in the first few hours. In short-term water soaking, the water repellency was greatest in coating C, followed by I, L, J, F, D, and K. As the interaction between time and coating was not significant ($\alpha = 0.05$) in the long-term water repellency test, the main effect, the coating, was analyzed as an isolated factor.

Coating C yielded the greatest WRE, followed by I, L, and J. The CLT samples were mainly composed of end grain that was in contact with water for 72 h. Similar results were found by Terzi *et al*. (2016) and Clausen *et al.* (2010) with WRE higher than 60% after 24 of water bath. Consequently, the satisfactory performance of these coatings was related to their ability to fill the voids present in wood cells. Coatings C, I, and J are water repellents composed of nonpolar molecules, which might have reduced the rate of water absorption and increased dimensional stability (Evans *et al*. 2016).

The efficiency of coating C was also observed for volumetric swelling and consequently dimensional stability expressed as ASE. The coating C specimens were 57% more dimensionally stable than the control ones. Bulian and Graystone (2009) noted that dimensional movement is a major issue that contributes to coating failure in exterior exposure. The trend observed in ASE was as follows: C > J > I > F > A = L > E = D = B > untreated > K = H = G.

Mold Growth

After 29 d of exposure to fungal spores, the greatest mold growth was observed on the control (pine) samples. No visible mold growth (zero) was observed for coating C (Table 5). Our findings contrast with Chen *et al*. (2009), that found no effect of coatings on preventing mold growth. Samples with coating J showed minimal amounts of mold (average mold grade of 1.4). However, compared to the other treatments, coating J had the worst performance.

Table 5. Average Mold Grades (± standard deviation) on Different Test Samples

Test Sample	Mold Grade
A	0.4±0.38 d
C	0.0±0.00 e
F	0.1±0.18d e
I	0.5±0.50 c
J	1.4±0.36 b
Control (CLT)	2.5±0.18 b
Control (pine)	6.0±0.00 a

Results followed by different letter within a column indicate that there is a significant difference ($p \leq 0.05$) as determined by ANOVA and Duncan's multiple range test.

Both coatings C and F contain iodopropynyl butyl carbamate (IPBC), which is an antimicrobial agent that likely prevented mold infection. Zhang *et al.* (2020) also found excellent mold inhibition when using IPBC on wooden materials. Because the test lasted only 29 d, it is expected that products with a lower score in mold testing (coatings C and F) would likely perform better in service.

Weight Loss by Decay Fungi

Paints and coatings are not intended to protect wood materials against fungal decay. However, several coating treatments had significant effects on the weight losses of the CLT samples from fungal growth.

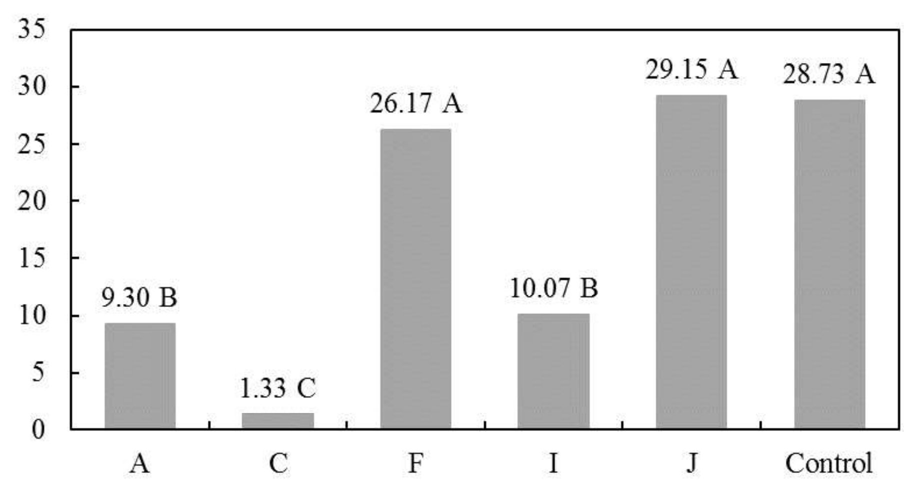

Fig. 4. Weight-loss-tested CLT samples exposed to *G. trabeum* after 18 weeks. Means with the same letter are not significantly different.

The weight losses of samples with coatings F and J were not statistically different from those of uncoated samples (Fig. 4). Both coatings were unable to protect the CLT from *G. trabeum* degradation. The high permeability of coating F may actually facilitate water absorption, which may lead to optimal conditions for fungal development. Coating J is a solvent-based product that is also liable to trap water through the end grain (Viitanen *et al*. 2010).

The lowest weight loss values were found on samples finished with coating C, followed by coatings A and I. Coating C's hydrophobicity prevented water intrusion, which most likely protected the samples against fungal colonization (Fig. 5). As de Meijer (2001) explains, the influence of coatings on fungal degradation is primarily through their influence in wood moisture content. However, if a coating is unable to exclude moisture, it might promote decay due to a low drying rate.

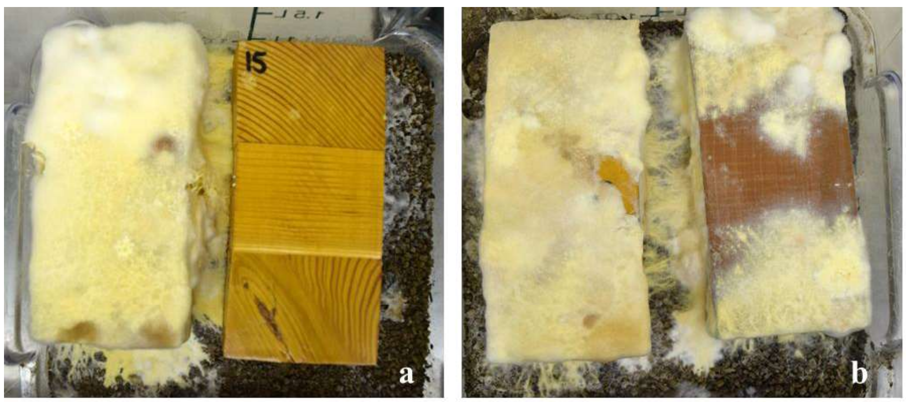

Fig. 5. Fungal growth on CLT samples: (a) Sample on the Left: coating J, on the right: coating C; (b) On the left: coating J, on the right: coating F

Coating C's ability to prevent decay in CLT exposed to harsh conditions (ground-contact, high humidity, aggressive decay fungi) is important, as CLT rapidly absorbs water (specifically from the end grain) and may be exposed to rain, high humidity, temperature changes during transport, storage, and construction. Currently, industrial CLT panels (access and crane-engineered mats) available in the market are intended for use in similar harsh conditions. Hydrophobic coatings such as those tested successfully here may be a temporary solution for short-term exposure of this type of CLT panel, particularly during construction and transport (Fig. 6).

It is important to reiterate that coatings are not intended to protect wood from decay fungi. Coatings are primarily used to protect wood from water, UV-light, blue-stain, and mold degradation (Varganici *et al.* 2020). Coating C's excellent performance in this test was likely because of the biocides present in its composition. Furthermore, protection of wood from decay fungi necessitates other protective methods such as pressure treatment and surface treatments paired with biocides.

Cappellazzi *et al*. (2020) described the dimensional constraints of mass timber that make its treatability impractical with current treating cylinders. Lim *et al*. (2020) tested the potential for manufacturing CLT from southern yellow pine lumber treated prior to layup with micronized copper azole, using various adhesives to bind the treated laminate layers. Lim *et al*. (2020) concluded that CLT panels glued with polyurethane have overall better performance than untreated CLT manufactured with the current method. Therefore, when

CLT is exposed to the outdoor elements (either above ground or in ground), it will likely be necessary to utilize treated products.

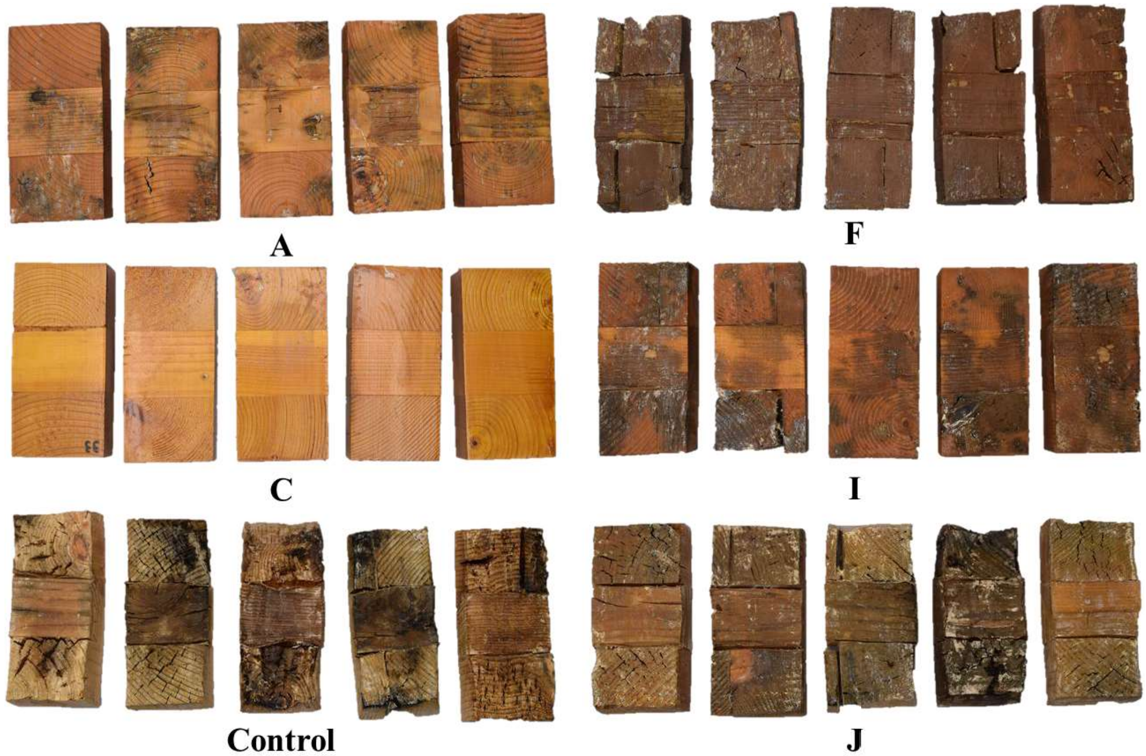

Fig. 6. Appearance of CLT samples after 18 weeks of exposure to *G. trabeum* in soil block test

CONCLUSIONS

1. Paints exhibited some water repellency efficacy, but they failed to prevent swelling over time. Among the twelve coatings tested, only five (A, C, F, I, and J) were able to prevent both water intrusion and dimensional changes. The performance of these coatings were associated with their ability to protect the end-grain of CLT samples by either penetrating into the wood cell or forming a physical and chemical barrier against water.
2. Coatings C and I promoted high water repellency on CLT, and the latter is the most effective in excluding moisture. Either one would be a reasonable solution for short-term exposure during transport, storage, or construction.
3. The high percentage of end-grain on the CLT samples made them highly absorbent. For this reason, coatings F and J did not offer any protection to water penetration which eventually contributed to decay fungal development. Coating C was found to offer the best protection against weight loss caused by *G. trabeum*. The physical barrier created by the film-forming nature of coating C protected the CLT samples from decay.
4. More research is needed to state the reason behind the excellent performance of coating C against the fungus used in this study. Surface treatments are not designed for protecting wood products against decay. However, when combined with biocides they

may be an adequate treatment that can be implemented in the CLT industry to increase durability of buildings and public safety.

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