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Evaluation of coatings used for prolonging the durability of cross-laminated timber against weathering and wood decay fungi

Gabrielly S Bobadilha

Evaluation of coatings used for prolonging the durability of cross-laminated timber against weathering and wood decay fungi

By

Gabrielly dos Santos Bobadilha

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Evaluation of coatings used for prolonging the durability of cross-laminated timber against weathering and wood decay fungi

By

Gabrielly dos Santos Bobadilha

Approved:

C. Elizabeth Stokes
(Major Professor)

H. Michael Barnes
(Committee Member)

Hyungsuk Thomas Lim
(Committee Member)

Grant Kirker
(Committee Member)

Rubin Shmulsky
(Graduate Coordinator)

George M. Hopper
Dean
College of Forest Resources

Name: Gabrielly dos Santos Bobadilha

Date of Degree: May 1, 2020

Institution: Mississippi State University

Major Field: Sustainable Bioproducts

Major professor: C. Elizabeth Stokes

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Candidate for Degree of Doctor of Philosophy

The aim of this study was to assess the durability of commercially available coatings on cross- laminated timber (CLT) during natural and artificial weathering and against wood decay fungus. The CLT samples coated with twelve coatings were tested based on their moisture exclusion, water repellency, volumetric swelling and anti-swelling efficiency. Among all the tested coatings, only five (A, C, F, I and J) were able to promote water repellency and limiting dimensional changes. The top five coatings were then tested on CLT blocks exposed to natural (Starkville-MS and Madison-WI) and artificial weathering conditions and brown-rot fungi (*G. trabeum*). Variables such as visual ratings, water uptake, color and gloss change were determined during both weathering procedures. Damage caused by *Gloeophyllum trabeum* on uncoated and coated CLT was analyzed based on visual appearance and weight loss. For the coatings C and F, the visual rakings and color change results indicated high consistency during outdoor exposure. The artificial weathering showed that coating C and F were the most resistant to chalking, lightness, color and gloss change. In the soil block test, coating C obtained satisfactory performance against *G. trabeum* with weight loss of 1.33%. Coatings F and J did not offer any

protection to water penetration, which eventually contributed to fungal development. For future, new coatings specifically designed for the protection of high percentages of end-grain in CLT panels should be a target of research and development.

Keywords: massive timber, protection, finishes.

DEDICATION

Dedicated to my lovely husband Dercilio, my parents Thereza and Livanio, and my second mom Ulda for all support and encouragement throughout this journey, you are wonderful.

"*We must all face the choice between what is right and what is easy*."

Albus Dumbledore

(J.K. Rowling 2000, Harry Potter and the Goblet of Fire)

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CHAPTER I

INTRODUCTION

Cross laminated timber (CLT) is a composite wood material suitable for middle to high-rise buildings due to its versatility (Van De Kuilen et al. 2011). In Europe, the use of CLT has been reported for at least two decades; it was introduced in Austria and Germany in the 1990's and has been used since for both residential and non-residential application (Crespell and Gagnon 2010). In North America, the CLT was introduced in the early 2000's and, as a new product, there are several practical challenges such as its resistance to weathering and wood decay (Pei et al. 2016).

Wood surfaces can lose their natural appearance due to repeated exposure to water and sun. Moisture within wood, according to Morris (1998), should be kept lower than 20% to avoid degradation. Sun exposure can seriously damage the surface of the wood material as surface photo-oxidation is catalyzed by ultraviolet radiation (Kataoka et al. 2007; Clausen 2010). Those two factors together are responsible for checking, splitting and wood cell erosion. In addition, such conditions facilitate the incidence of fungal growth on wood (Shupe et al. 2008).

Fungi are one of the principal agents of wood deterioration (along with bacteria, termites, and insects). Stains and molds are distinguished from wood-decay fungi in that wood-staining fungi do not affect wood strength properties; however, they produce a wide range of color effects or different stains (Shupe et al. 2008). They also can increase the porosity of wood, which can result in over-absorption of resin, paint, or wood preservative during subsequent processing. As

the wood becomes more porous, it also becomes more wettable leading to higher susceptibility to wood-decay fungi (Clausen 2010). Thus, a way to control the effects of weathering and consequently wood-decay is by employing protective coatings.

According to Ekstedt (2002) coatings for exposed wood have two purposes - one is to provide good surface appearance and color, and the other is to protect the wood against both degradation and deterioration by abiotic and biotic agents. The main purpose of this work was to assess a durable coating from among those currently available to the public for CLT exposed to both weathering and fungal decay. The principal hypothesis of the research project was:

H_1: CLT protected by coatings would have different behaviors in terms of resistance to weathering and wood decay when exposed to external factors.

Therefore, this project contained several specific objectives:

- Select a range of coatings according to their performance in water repellency (WRE) and anti-swelling efficiency (ASE) tests.
- Expose uncoated and coated CLT samples to both artificial and natural weathering with the latter being performed in two different sites, one in Madison-WI and the other in Starkville, MS, and to a commonly occurring wood decay fungus *Gloeophyllum trabeum* (Pers.) Murrill, MAD 612.
- Monitor weathering coatings performance over time for each month up to 6 months by comparing color change using spectrophotometry based on CIE L*a*b* color system, surface luster and macroscopic evaluations, such as checks, cracks, chalking, erosion, and mold growth.
- Evaluate the resistance of CLT to wood mold and decay fungi by visual ratings and weight loss respectively.

CHAPTER II

LITERATURE REVIEW

2.1 Cross-laminated timber

Cross-laminated timber is one of the newest innovations in engineered wood products (EWP), also named Cross-Lam or X-Lam (Mohammad et al. 2012). CLT is a massive timber product, with layers organized crosswise at right angles (usually in odd number) glued together (Crespell and Gagnon 2010).

In the 90's a few companies in Switzerland started producing CLT panels using proprietary approaches (AlSayegh 2012). In the early 2000s, the production of CLT panels in Europe, particularly Austria, dramatically increased after public initiatives on sustainable solutions, higher efficiency in construction, changes in building codes, and improvements in marketing and distribution channels (FPInnovations 2010).

The ANSI/APA PRG 320 Standard for performance-rated cross laminated timber, is used for standardization of CLT quality, manufacturing and structural properties for structural building applications. In North America the use of CLT in construction is rapidly growing. The International Market, Analysis, Research and Consulting (IMARC) group (2019) reported that the global cross-laminated timber market generated US$ 664 million in 2018. In 2024, it is expected that CLT will expand reaching US$ 1.457 billion of the global economy.

CLT panels are manufactured with three to nine layers with thickness ranging between 50-500mm and up to 13.5m in length (Ramage et al. 2017). The APA- The Engineered Wood

Association (2018) recommends that any softwood lumber species or species combinations shall be used as long as they are accepted by American Lumber Standards Committee (ALSC) and are under PS 20 code (NIST, 2015). Additionally, according to the National Design Specification for Wood Construction (NDS) they are required to have a minimum specific gravity of 0.35 (American Wood Council, 2018). The same species or mixture of species should be used within a single layer and surrounding layers may be composed of different species or combinations of species.

Because CLT is made of wood, it has multiple environmental benefits. Trees grow naturally and wood is a renewable material. John et al (2009) pointed out that CLT-related carbon sequestration capacity would enable a building to operate without CO_2 emissions for the first 12 years of its life. Apart from its sustainable properties, CLT has multiple advantages compared to other timber products and mineral based building materials.

The cross-wise arrangement of CLT promotes dimensional stability allowing it to compete with traditional products in the market such as, concrete, steel, and masonry (Crespell and Gagnon 2011). Since CLT is appropriate for mid- to high-rise buildings, it has been used worldwide in the public sector as well as single-family and multi-dwelling residential units (Kremer and Symmons 2015).

CLT elements are prefabricated with pre-cut openings for doors, windows, stairs, service channels and ducts, allowing it to be shipped from manufacturer to construction site ready to be put into place. Because, they are easily and rapidly erected into place, the construction schedule is reduced (Evans, 2013). Consequently, CLT constructions have lower capital cost, faster project turnaround, and potentially lower insurance costs. The lower price of materials (see Table 2.1) contributes to CLT cost effectiveness (Mallo and Espinoza 2014). Crespell and Gagnon

(2010) reported that the material cost of CLT structure was around 15% less than concrete, steel and masonry mid-rise residential building. They also found out that the cost for non-residential and low-rise buildings construction can be up to 50% less than non-wood buildings.

Table 2.1 Cost estimation analysis including construction options with cost estimation developed by Mallo and Espinoza (2016).

Element	Concrete/Steel option	CLT options	
		Basic CLT Manufacturer 1	Basic CLT Manufacturer 2
	Concrete walls/roof, steel beams, light-steel frame	CLT walls/roof, steel beams, light-steel frame	
Structural walls	$1,071,680	$624,417	$414,901
Concrete slabs	$256,416	$256,416	$256,416
Roof system	$600,975	$427,809	$289,339
Interior walls	$155,304	$155,304	$155,304
Cost per sqft	$64	$64	$55

CLT's thick cross-section provides valuable thermal performance and fire resistance. The thermal performance of wood is measured by U-value (coefficient of heat transfer) and R-value (insulating ability). Materials with higher R-values are preferred because they have higher insulating ability (Mallo and Espinoza 2015). For example, R-value for wood is 1.25 per inch of thickness. Consequently, a 7-inch-thick CLT panel would yield an R-value of 8.75 (Evans 2013). In fire resistance tests, CLT elements perform well because they char at slow and predictable rate (Crespell and Gagnon 2010). This characteristic provides dimensional stability and strength to the structural element without collapsing in an abrupt way, potentially allowing time to the evacuation of the occupants from the building.

The dimensional stability and rigidity of CLT elements make them appropriate for mid to high-rise buildings with valuable resilience to earthquakes (Bolvardi 2018). A study by Popovski et al (2011) showed that CLT structures subjected to a severe earthquake simulation (magnitude

of 7.2 on the Richter scale) had no permanent deformation, with a maximum inter-story drift of 1.5 inches and maximum lateral deformation of 12 inches after the test.

Regardless of the many advantages of using wood structural systems, there is a concern about their durability as there is for any other construction material. Wang et al (2018) pointed out that any material can experience some type of moisture issue, which might be caused by vapor condensation, roof leaks, failures at building envelope penetration and 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 numerous pieces of timber needed for assembling CLT contribute to water absorption throughout the panel. Eventually with short-term wetting or high relative humidity (RH ranging from 80% to 95%), this can result in dimensional changes, moisture damage, and microbial growth (Schmidt and Riggio 2019). Even the speed at which CLT panels are assembled on site can be critical due to exposure to weather elements for periods of time. Furthermore, moisture management at all stages of building construction is the key to prolonging the lifetime of mass timber buildings (Wang 2016).

According to CLT book of standards, CLT panels are not designed for exterior exposure since they are highly susceptible to moisture uptake (Crespell and Gagnon 2010). Most of the CLT based architecture projects that were developed or are under development in the US contain some type of envelope protection. However, there are exceptions such as Sauter Timber (TN), Tacoma East Side Community Center (WA), Salvage Swings (AK and NY), and Mc Donald's Flagship, Chicago (IL) (Esler 2015; Hendel 2018; Franklin 2019; ThinkWood 2019). The issue with these buildings is that they are made of unpreserved wood materials, that may be deteriorate faster by biotic and abiotic agents specifically in areas with high humid and warm temperatures.

2.2 Weathering

Weathering performance of CLT in many parts of the country is still unknown (APA 2016). To continue expansion of CLT use in mid and high-rise construction market, more research should be done to implement proper codes for managing moisture and weathering (Crespell and Gagnon 2010). The term weathering is used to describe any type of surface degradation that occurs on wood in response to environmental factors (Williams et al 2001). Weathering of wood is a consequence of photolytic, oxidation and hydrolytic reactions, occurring in lignin (photo-oxidation) and in hemicellulose of wood (photo-oxidation and hydrolysis) (Reinprecht 2016; Feist and Hon 1984; Williams et al. 2001).

Unprotected wood is susceptible to decay, stain, mildew, and warp, once successive exposure to water and sun can degrade the surface of wood, with the surface becoming coarser, including crack, splits and wood cell erosion (Koch 1972; Shupe et al. 2008). Ozgenc and Yildiz (2016) studied weather resistance of oriental spruce timbers and concluded that climate conditions, environmental pollution, and biological pests, modify the surface roughness of the wood surface. This process happens through photo-oxidation of the surface activated by ultraviolet (UV) radiation in sunlight, and it is also influenced by rain, oscillation in temperature and moisture content, and abrasion by wind-blown particles (Williams 1999).

Williams (2005) gives four abiotic mechanisms that affect the wood surface in Table 2.2Table 2.2.

Table 2.2 Mechanisms of weathering degradation (modified version, with only abiotic factors).

Weathering factor	Description
Irradiation	Photo-oxidation of the polymers present in wood
	Destruction of lignin leading to delamination
	Generation of secondary chromophores leading to wood photo yellowing
Water	Surface leaching
	Stress in the material leading to fractures, splits and checks
Heat	Accelerates photo-degradation
	Accelerates hydrolysis
Atmosphere	Oxygen and pollutants
	Sand

2.2.2 Environmental factors affecting weathering of wood

2.2.2.1 Irradiation

Solar radiation is the principal environmental factor in charge of the surface weathering of wood leading to photodegradation (Rowel 2013). Even though photodegradation has been a popular research topic since the 1960s, its action mechanism still not fully understood (Tarkow et al. 1966; Cogulet et al. 2018). Photodegradation begins with the absorption of a photon, a molecule in an excited state (Rabek 1994; Williams 2005). The chemical groups affected are chromophoric and phenolic, and the result is the formation of free radicals (Moore and Owen 2001). Later, these photons modify the physical and chemical properties of the surface layer of the wood (Csanády et al. 2015).

UV light, specifically UVB (280-320 nm) is more active than visible light and able to split the carbon-carbon, carbon-oxygen, and carbon-hydrogen bonds that bind the polymeric components of wood, cellulose, hemicelluloses, lignin, and extractives (Rowel 2013). Photodegradation is usually seen on the wood surfaces where color is the most apparent affected parameter (Csanády et al. 2015).

As wood extractives determine the color of the wood, they are modified upon exposure to sunlight and lighten or darken color (Nzokou and Kamdem 2006). Tolvaj et al. (2012) found out that extractives of black locust (*Robinia pseudoacacia*) were highly sensitive to light irradiation. As a consequence, these extractives were quickly degraded at the first period of the light irradiation. Lignin, however, is degraded by exposure to ultra-violet light (Kataoka et. al. 2007). Panshin and De Zeeuw (1980) pointed out that, as weathering effects advance, all woods acquire a silvery-gray color, with gray layers varying from 0.003 to 0.01 inch in depth. After extractive and lignin degradation, the remaining composition of the wood surface is the partially loosened fibers of cellulose and hemicellulose.

Laskowska et al. (2016) found that UV radiation had significant effect on wetting property of the cedar and pine sapwood determined by contact angle. The wood surface of these two species became more susceptible to wetting. Furthermore, color alteration of the surface is followed by other changes that influence the wettability and surface chemistry of the wood (Williams 1999). According to Koch (1972), chemical modifications in the gray layers caused by weathering effects result in surface roughness and erosion, which may reduce board thickness over years of exposure.

2.2.2.2 Water

Wood is a hygroscopic material in equilibrium with air relative humidity (RH). Moisture content (MC) of wood influence its physical properties and durability. Wood swells and shrinks as the MC rises and decreases respectively before reaching equilibrium moisture content (EMC) (Panshin and De Zeeuw 1980; Glass et al. 2013). As a result, changes in wood MC lead to deformation in diverse directions: radial, tangential, and longitudinal (AlSayegh 2012). Bank and

Evans (1984) reported that pine lost 10-30% of tensile strength and 20-60% of toughness due to 2 months of exposure to deionized water and temperature between 25-65 °C.

Wood composites are susceptible to dimensional changes due to water intrusion (Rowel 2013). According to Carll and Wiedenhoeft (2009), the integrity, strength of bonded wood, and progressive deflection of wood composites can be impaired by swelling-induced stresses caused by moisture, and by repetitive cycles of drying and wetting. Even mechanical connections may be compromised by moisture exposure. Mohammad et al. (2013) pointed out that CLT connections should be designed to prevent moisture penetration between metal plates and CLT walls as water may get trapped and cause potential damage.

Since CLT is a massive timber product, it also can buffer moisture related to its volume. Rapidly, the moisture absorbing capability gets higher than that of other wooden materials (Öberg and Wiege 2018). Short-term moistening or high relative humidity (RH between 80-95%) can facilitate mold growth. Mold damage can usually be washed out, but sources of moisture must be detected and eliminated to prevent recurrent damage (Schmidt and Riggio 2019).

2.2.2.3 Heat

The thermal degradation of wood is a set of chemical reactions that starts right after energy activation by heating (Reinprecht 2016). Temperature may not be as critical as UV light or water, but high temperature increases the intensity of photochemical and oxidative reactions (Feist and Hon 1984). Evans (2008) pointed out that wood exposed to tropical weather and consequently higher temperatures is unlikely to reach lignin's glass transition temperature or temperatures that cause significant structural degradation of wood chemical components. Tolvaj et al. (2012) evaluated thermal degradation of wood exposed to light irradiation, and found that

degradation of lignin was negligible for samples exposed to heat. However, they noticed that color change was influenced by thermal degradation.

Temperature fluctuations induce thermal gradient formation between the wood surface layer and inner layer (particularly in materials with lower thermal conductivity, e.g. CLT), which can result in degradation of the mechanical properties of the material and formation of fine cracks (Moncmanová 2017). Heat accelerates the surface drying of wood generating stresses that results in checking (Evans 2008). Low temperature and repeated cycles of freezing and thawing may also contribute to wood checking (Feist and Hon 1984).

2.2.2.4 Atmospheric pollutants

Exposure to atmospheric pollutants accelerates the damages caused by weathering (Moncmanová 2017). The major pollutants of concern are dust, smoke particles, and volatile pollutants (Evans 2008). Small particles such as sand can be fixed in surface checks and weaken the wood fiber in contact with the particles, through swelling and shrinking (Feist and Hon 1984).

A typical example is degradation by acid rain, which contains sulphur dioxide, nitrogen oxides and the acids produced from them (e.g. H_2SO_3, H_2SO_4 and HNO_3) (Reinprecht 2016). Williams (1987) studied the effect of acid treatment on the erosion rate of western redcedar by using accelerated weathering techniques. The samples were soaked into nitric and sulfuric acids at different pH levels. Soaked samples had 10% increase in erosion rate when compared to unsoaked samples at pH 3.0.

2.2.3 Weathering evaluations

2.2.3.1 Natural weathering

The changes caused by weathering are expressed on the aesthetic of the material (Rüther 2011). Weathering tests provide important information on the service life of wood, wood-based materials and finishes. The ISO 15686-1 (2000) standard defines service life of wood as "period of time after installation which a building or its parts meets the performance requirements". Service life prediction of wooden materials is challenging because of the many factors involved such as durability of material, protection applied, and climate conditions (Isaksson and Thelandersson 2013).

Natural weathering tests are performed to evaluate the durability of a certain product at a certain location (climate condition). These tests are important because all the environment factors are considered. Many studies have been performed to determine the lifetime of wood and wood-based materials exposed to natural weathering (Feist and Hon 1984; Feist 1990; Derbyshire et al. 1995a, b; Yata and Tamura 1995; Evans 1996). They all reported color change, surface roughness, checks, cracks and erosion caused by abiotic factors in interaction with stain and mold fungi.

Although outdoor tests provide valuable information of a product, they present disadvantages. Natural weathering tests are highly dependent on the location, starting date and duration of test, which can impair the reproducibility of the test. Additionally, most of the published works described wood and wood-based materials exposed for less than three years (Nejad and Cooper 2011; Del Menezzi et al. 2008; Williams et al. 2001) which does not encompass the entire service life of a wood product. In other words, frequently, end users are not able to predict the service life of a product only through natural weathering test.

2.2.3.2 Artificial weathering

The speed and pattern of wood surface modification are difficult to predict and are rarely considered in the initial phases of building design (Petrillo et al. 2018). Artificial weathering testers use artificial light sources to measure the resistance of materials to UV degradation. These tests allow users to save time and quickly understand the weathering effects on the aesthetic properties of the wood and wood coatings (Liu et al. 2019; Teacă et al. 2013; Tolvaj and Mitsui 2005).

As all the weathering factors cannot be simulated collectively (such as degradation by UV light, wetting by liquid water and discoloration by mold and stain fungi), accelerated tests usually are focused on the effects of UV light, moisture and temperature (Teacă et al. 2013). The results obtained from accelerated tests are further used to estimate service life of materials.

The advantages of using accelerated weathering test are associated with reproducibility, controllable conditions, and probable correlation with natural weathering of uncoated and coated wood (Feist 1988). According to Arnold et. al. (1991) artificial weathering tests can accelerate the effects of natural weathering from 5 to 20 times depending on the exposure conditions set. Although accelerated weathering tests are important to determine the mechanisms of photo degradation and moisture relations caution must be taken to avoid extrapolation of data in the prediction of natural performance (Clark and Munro 1983).

2.3 Fungi

Wood exposed to natural weathering is likely to be attacked by biological pests due to depolymerization of lignin and hemicelluloses. These polymers degrade to low molecular weight substances which are more susceptible to deterioration by microorganisms (Reinprecht 2016). One of the major deteriorating agents of wood are fungi. Three types of fungi are usually

responsible for damages - decay fungi, sapwood stains, and molds (Reinprecht 2016). Molds and fungal stains usually colonize on sapwood and may be cottony or downy growth, varying in color from white to shades of yellow, brown-red, purple-blue, and green to black (Panshin and De Zeew 1980). Decay fungi cause significant impairment of wood, usually to a point that the mechanical and physical properties are completely compromised.

2.3.1 Mold

Microbial disfigurement of coated wooden surfaces is considered to be a major maintenance concern. Bjurmann (1988) pointed out mold growth might facilitate the attack by decay fungi. Several investigators have shown that mold fungi can penetrate the coating film and thereby colonize the interface between the finish and wood (Gobakken and Westin 2008; Bardage,1997; Sharpe and Dickinson 1992; Bravery and Miller, 1980; Winters et al. 1978).

At mild temperature and favorable moisture, mold fungi are likely to establish and develop quickly in the sapwood of logs and lumber (Highley 2010). Tsongas and Riordan (2016) pointed out that mold growth occurs in response to the conditions on the surface (water and food for a fungus), which include surface water activity or the relative humidity of the air on the surface, and the duration of wetting. Even though mold and stains do not degrade the wood cell wall, they need to feed themselves from the food found within the lumen such as sugars and starch (Bowyer et. al. 2007).

Mold is a significant issue due to the possibility of occurring at any manufacturing stage of wood products or when in use if the product is wet enough (Highley 2010). Although, properly kiln or air-dried lumber is too dry to be infested my molds and stain fungi, they can penetrate the end grain of fresh cut logs and lumber, or seasoned lumber that was moistened within 24 hours between 10 to 38°C (Verral and Amburgey, 1979). Panshin and De Zeeuw

(1980) pointed out that infestation of mycelium occurs on boards due to the blockage of air circulation between layers. The results of mold infestation are the decreasing of the surface quality (higher porosity and undesirable stain) and consequently devaluation of the wood product.

According to Highley (2010) the way to differentiate molds and fungal staining is by the depth of discoloration. Usually, the difference is that blue stain goes further into the wood and may not be removed by cleaning the surface (Highley 2010). Molds are commonly found on surfaces and interior of buildings, and generally belong to the phyla of Ascomycetes or Deuteromycetes (Stewart et al. 1979). Schmidt (2006) pointed out that molds may have different physiological response regarding to temperature, water activity, and pH value which influence their colonization and damages to a variety of materials. On softwoods, mold can deeply penetrate the wood but in hardwood the damage is often just beneath the wood surface (Highley 2010).

Wilkinson (1979) describes mold as a fungus that does not attack wood, as it penetrates only few millimeters into the wood living on parenchyma cells (sugars, starch, protein), particularly in the rays. Since they do not degrade lignified cell walls, the wood strength properties are only slightly affected (Schmidt 2006). However, they do affect the water absorbency of wood which can lead to over-absorption of finishes, paint, glue, and preservatives. In addition, higher absorbency can increase the wood's moisture content, resulting in later colonization by wood-decay fungi (Clausen 2010).

As mold-infested wood is an unmarketable product, its consequences are mainly economical. For instance, wood for wall paneling with mold is unsuitable, as the color spots cannot be removed, and paints would just mask them (Schmidt 2006). There are also some

discussions of molds causing health issues, due to harmful aflatoxins found in some mold species (Meister and Springer 2004).

2.3.2 Decay fungi

Decay fungi are the most damaging organisms to wood, whose growth depends on moisture, mild temperature, and oxygen availability (Lebow and Highley 2008). Consequently, methods for controlling wood-decay are based on restricting one or more of these conditions (Panshin and De Zeeuw 1980; Shmulsky and Jones 2011).

Decay fungi need wood moisture content of at least 20% to grow, and for initial spore germination 30% of moisture content is generally required (Zabel and Morrell 1992; Morris 1998; Highley 1999; Lebow and Highley 2008). Decay fungi do not typically colonize wood with moisture below fiber saturation point although previously established fungi are not greatly affected by decreasing humidity; once colonized wood-decaying fungi are able to bring water to the wooden product via mycelia (Lebow and Highley 2008; Reinprecht 2016).

According to Clausen (2010), decay usually occurs when temperature is between 10°C to 35°C. The author also points out that, decay needs moisture content above the fiber saturation point to progress. However, as CLT has been planned to be used for structural purposes and some exterior uses, exposure of this material to inclement weather conditions may lead to fungal deterioration. Panshin and De Zeew (1980) reported that in the South of United States, wood tends to decay more quickly given the climate conditions. In the North, even with water availability, wood decay happens slowly because of adverse temperature conditions.

Wood-decaying fungi tend to attack either heartwood or sapwood in most wood species (Clausen 2010). Wood-destroying fungi are classified as brown rots, white rots, and soft rots.

Both brown and white rots are caused by Basidiomycete fungi, while soft rot is produced by Ascomycetes and Deuteromycetes (Panshin and De Zeeuw 1980).

Brown rot fungi are responsible for decomposing carbohydrates such as cellulose and hemicellulose from wood, but lignin only at a minimum rate leaving a brown, oxidized appearance (Rowell 2013; Reinprecht 2016). Brown rot fungi preferentially attack softwoods, but they may also attack hardwood logs, with the wood's strength properties decreasing rapidly as the attack progresses (Clausen 2010). Later, the cross-grain cracks, the wood shrinks and collapses, and at last crumbles (Rowell 2013). In temperate climates, brown rot fungi are the most important agent of destruction in wood buildings (Morris 1998).

According to Morris (1998) white rot fungi are more frequent in hardwoods where they are responsible for decomposing lignin, hemicellulose, and cellulose leaving the remaining residue with a paler aspect. The strength properties of woods attacked by these fungi decrease more gradually than brown rot infested wood, however, white rots give a spongy texture to the wood (Rowell 2013).

Deterioration caused by fungi affect the molecular, anatomical, and geometry structural levels of attacked wood (Reinprecht 2016). As the structural modifications are related to many physical and mechanical properties of damaged wood, some changes occur on wood density, permeability, hygroscopicity, electric resistance, surface conductivity and acoustic properties (Bech-Andersen 1995; Reinprecht and Hibky 2011; Reinprecht 2016).

2.4 Coatings

In the South where the temperature and humidity are elevated, color and appearance of wood are rapidly modified by weathering and fungi that can grow on the surface (Koch 1972). The capacity of protection systems to impede the weathering effects on wood surfaces is linked

to the properties of the wood substrate, especially density and shrinkage characteristics. Also, the effectiveness of treatment at preventing wood photodegradation and surface stress may be provoked by the wood substrate checking (Rowell 2013).

The most used method to protect wood from weathering effects is the application of paints, varnishes, stains, or water repellent coatings (de Meijer et al. 2001). These are used on the surface of the wood not only for design and appearance but also for extending its durability (Dilik et. al. 2015).

Coatings have enormous importance in the protection of wood against weather influences responsible for the degradation of mechanical or chemical properties (de Meijer et al. 2001). Water repellent preservatives prevent against microorganisms' deterioration and reduce moisture uptake by capillary action (Bulian and Graystone 2009). According to Pánek et al. (2017), tested hydrophobic coatings should be used for exterior applications without direct rainwater contact. They also suggest that when the rainwater contact is unavoidable, multilayer coatings could help to keep the natural appearance of wood for a long time.

The coating performance on wood exposed to weather is influenced by diverse stressing factors such as photoirradiation, thermal radiation, mechanical impact, the presence of moisture and microorganisms resulting in different weathering effects such as: photochemical degradation, loss of surface integrity (cracking, flaking or erosion) and discoloration (Reinprecht 2016; Feist 1983). Moreover, the type and intensity of the degradation is greatly affected by factors such as time and conditions during weathering, wood properties, design of the wooden structure, the physical and chemical properties of the coating itself, the type of application, the film thickness, and the color of the coating and the maintenance (de Meijer et al. 2001).

According to Petrič (2013), several properties of the wood can be improved by surface protection methods. Wood coatings are separated as either film forming or penetrating types (Williams et al. 2001). Film-forming finishes such as paints and solid-body stains have pigments that screen wood from photo irradiation and, as they promote a barrier over the wood surface, they protect against wetting and erosion as well (Feist 1990). MacLeod et al. (1995) pointed out that clear film forming coatings lose their efficiency due to weathering exposure, mainly due to photodegradation. Penetrating finishes, constitute oils, water repellents, stains, preservatives and surface treatments (Feist 1990). Laughnan (1956) noticed that penetrating finishes are more effective than film forming and, require less maintenance, making them the choice for wood exposed outdoors.

Wood exposed to weathering and fungi is likely to change its surface color, texture and strength (Shmulsky and Jones 2011). Whereas photodegradation and cycles of dry and wet weather bring changes on the surface of the wood, fungal attack (that is often a result of these factors combined) can have more drastic impact in the wood (Rowel 2013). According to Morrel (2005), wood decay is responsible for early failure of wood and wood composites, also replacing infested wood and wood materials accounts for 10% of the global lumber trade. Coatings can be a suitable option against weather and consequently fungal infestation.

The purpose of this work was to determine the performance and appearance of cross laminated timber using durable exterior wood coatings commercialized in North America. To accomplish that, a wide range of exterior wood finishes including both water-based and solvent-based were investigated.

CHAPTER III

MATERIALS AND METHODS

3.1 Preliminary test

To determine water repellency effectiveness (WRE) and anti-swelling efficiency (ASE), two CLT panels were manufactured. Six (6) number 2 2x4 southern yellow pine (SYP) lumbers were planned, trimmed and cut on two different lengths: out-layer 76.2 cm, and core-layer 30.5 cm (Figure 3.1). The layers were glued together with polyurethane (PUR) and cold pressed for 3 hours at pressure of 107 psi.

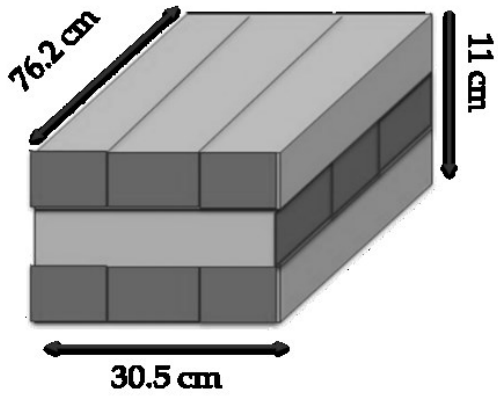

Figure 3.1 Cross laminated timber panels dimensions and design.

Sixty-five (65) (free of knots, resin pockets, cracks, and end joints) samples measuring $11\times5\times2.5cm^3$ (length, width, and height) were selected to test based on absence of defects, similarity in size and direction of growth ring and wood density. The samples were randomized

and distributed to each treatment. The treatments consisted of 12 US market water and solvent based coatings/stains: transparent, semi-transparent and white paint. The specimens were coated according to manufacture instructions and a set of samples was left uncoated (Table 3.1).

Table 3.1 Description of selected coating systems

Coating	Base	Type	Color	Resin Type	Replicates
A	Water	Transparent	Natural	Alkyd/Acrylic	6
B	Water	Transparent	Natural	Acrylic	6
C	Water	Transparent	Clear	Alkyd/Acrylic	6
D	Solvent	Transparent	Natural	Alkyd	6
E	Solvent	Transparent	Natural	Alkyd	6
F	Water	Semitransparent	Deep gold	Acrylic	6
G	Water	Semitransparent	Cedar	Acrylic	6
H	Water	Semitransparent	Cedar	Alkyd/Acrylic	6
I	Solvent	Semitransparent	Redwood	Alkyd	6
J	Solvent	Semitransparent	Cedar	Alkyd	6
K	Water	Paint	White	Acrylic	6
L	Water	Paint	White	Alkyd/Acrylic	6
Control	N/A	N/A	N/A	N/A	6

After being coated the samples were air-dried, weighed, and conditioned in an environmental chamber at 66% relative humidity and 24°C (12% equilibrium moisture content) until the samples reached a consistent weight. Then the moisture excluding efficiency (MEE) was calculated as follows (Equation 3.1):

$$MEE(\%) = \frac{M_U - M_T}{M_U} \times 100 \quad (3.1)$$

Where,

MEE= Moisture excluding efficiency; M_U= moisture uptake of untreated samples; M_T= moisture uptake of treated samples.

To determine the water uptake capacity, after being conditioned and weighed, the samples were submerged into a water bath and weighed in the following intervals: 30m, 1h, 2h, 24h, 48h, and 72h. The water repellency effectiveness (WRE) was determined using equation 3.2, defined as:

$$WRE(\%) = \frac{W_U - W_T}{W_U} \times 100 \quad (3.2)$$

Where,

WRE= Water repellency effectiveness; W_U= Water uptake of untreated samples; W_T= Water uptake of treated samples

The changes in dimension due to moisture uptake were determined by measuring the volume for periods of 24, 48 and 72 h. The volume of the CLT pieces were obtained by caliper (measurement at same spot for error reduction), and volumetric swelling coefficient was calculated from Equation 3.3.

$$S(\%) = \frac{V_2 - V_1}{V_1} \quad (3.3)$$

Where

S= volumetric swelling coefficient; V_2= wood volume after humidity conditioning or wetting with water; V_1= wood volume of oven-dried sample before conditioning or wetting.

Anti-swelling efficiency was calculated for each time based on the volumetric swelling (Equation 3.4)

$$ASE(\%) = \frac{S_U - S_T}{S_U} \quad (3.4)$$

Where

ASE= reduction in swelling efficiency resulting from a treatment; S_U= untreated volumetric swelling coefficient; S_T= treated volumetric swelling coefficient

The results obtained from these tests were used to select the best coatings based on their resistance to water intrusion and dimensional change.

3.2 Weathering

3.2.1 Samples preparation and coating systems

Blocks with dimensions of 15 x 14 x 11cm^3 (length, width, and height) were prepared from three-ply (three layers) CLT panels (SmartLam LLC; Whitefish, MT) made from hemlock-fir species for weathering exposure. The samples were conditioned to a consistent weight in an environmental chamber with a moisture content of 12%, sanded by sandpaper in a longitudinal direction, and sorted based on density and visual appearance. Samples that contained the fewest end joints and other defects (knots, resin pockets, and cracks) were selected to decrease variability among treatments.

The top five commercial wood coatings were selected from the preliminary tests and their description are given in Table 3.2.

Table 3.2 Specification of tested coating systems

Treatment	Coating or surface description	Resin Type	No. of layers
A	WB, transparent penetrating wood finish	Alkyd/Acrylic	2
C	WB[1], transparent, UV resistant	Alkyd/Acrylic	3
F	WB, Semi-transparent, water and UV resistant	Acrylic	2
I	OB[2], transparent, mildew and water resistant	Alkyd	2
J	OB, semitransparent and water repellent	Alkyd	1
Control	Reference without coating	x	x

WB[1]= water based; OB[2]= Oil based.

The coatings were applied by brush on CLT samples in accordance with technical data supplied by manufacturer. For the natural weathering test, six CLT specimens were applied for each treatment within the two blocks (location) giving a total number of 72 samples. For the artificial weathering test a total of 36 CLT samples were used 3 replicates per treatment per exposure cycles (2). Before being exposed the samples were conditioned at 66% relative humidity and 24°C to constant weight.

3.2.2 Natural and artificial weathering

CLT blocks were exposed for six months (June-December 2019) in two locations, one in the northern U.S. at Madison, WI and the other in the southeast in Starkville, MS. The exposure site in Madison is located at the Forest Products Laboratory (FPL) Valley View field site and the one in Starkville is located at the Department of Sustainable Bioproducts (Figure 3.2).

(a) (b)

Figure 3.2 Outdoor weathering test set up (a) Madison, WI and (b) Starkville, MS.

The racks were constructed with garden mesh to avoid water trapping under the samples bottom. An overview of the climatic conditions during 6 months of natural weathering exposure is displayed in Table 3.3. A set of samples per location composed of one sample per treatment left unexposed in an environmental chamber for further comparison.

Table 3.3 Weather conditions at Starkville MS, and Madison WI during natural outdoor exposure of coated and uncoated CLT samples (National Oceanic and Atmospheric Administration -NOAA, 2019.

	Starkville			
2019	Weather conditions			
Months	Mean temperature (°C)	Total precipitation (mm)	Mean radiation (kW-h/m^2)	Total snow (mm)
Jun	26	211.6	6.3	-
Jul	27.5	271.3	6.5	-
Aug	27.5	140.5	6.4	-
Sept	27.5	1	6.1	-
Oct	19.2	278.4	4.5	-
Nov	9.3	93.7	3.3	-
Dec	9.9	172.5	2.7	
	Madison			
Jun	19.2	131.1	6.8	-
Jul	24	146.6	6.7	-
Aug	20.3	72.4	6	-
Sept	18.9	172.7	4.9	-
Oct	9.2	140.7	3.4	205.7
Nov	-0.5	66.8	2.1	193.0
Dec	-1.1	38.6	1.6	73.7

The artificial weathering test was conducted in a weathering apparatus which simulated exterior conditions by alternating cycles of irradiation and water spray. The unit was equipped with UV-A lamps ($W \cdot m^{-2}$ at 340 nm) maintaining constant temperature of 26°C. The samples were exposed to weathering cycles of set 12 hours of UV-light irradiation and 12 hours of water spray (0.36 Lpm) for 15 days (360h) and 75 days (1800h). The weathering tester is shown in Figure 3.3.

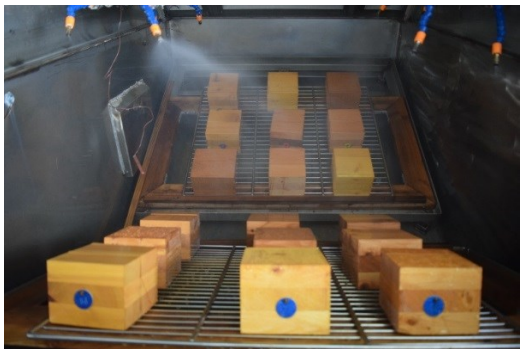

Figure 3.3 Weathering apparatus containing blocks fixed at 45° angles to holding racks.

The outdoor weathering samples were assessed every month and artificial weathering samples after each cycle for macroscopic evaluation (Table 3.4) such as checks, cracks, chalking, erosion, and mold growth (ASTM D660, ASTM D661, ASTM D662, and ASTM D3274). The visual ratings were given based on comparisons to reference pictures displayed on the standards. Checks and cracks of coatings were not perceived, for this reason only the types of coating failure registered were chalking and or flaking, and consequent erosion.

Table 3.4 Visual rating scale for fungal growth and other physical characteristics, based on ASTM testing standards.

Description	Rating
Fungal growth	(0-10)[1]
Checking, cracking, blistering, flaking, chalking, erosion	(2, 4, 6, 8, 10)[2]

[1] 0 full coverage and 10 no fungal growth.
[2] 2 severe failure and 10 no defects.

The chalking evaluation was based on samples that were somewhat faded or washed off from the wood surface compared to unexposed samples. The chalking evaluation is highly subjective and weather dependable. For this reason, we compared the samples surface before and after exposure using high definition pictures. Most of the coatings started fading as time

progressed (Figure 3.4). Erosion was defined as complete removal of coating leaving surface unprotected.

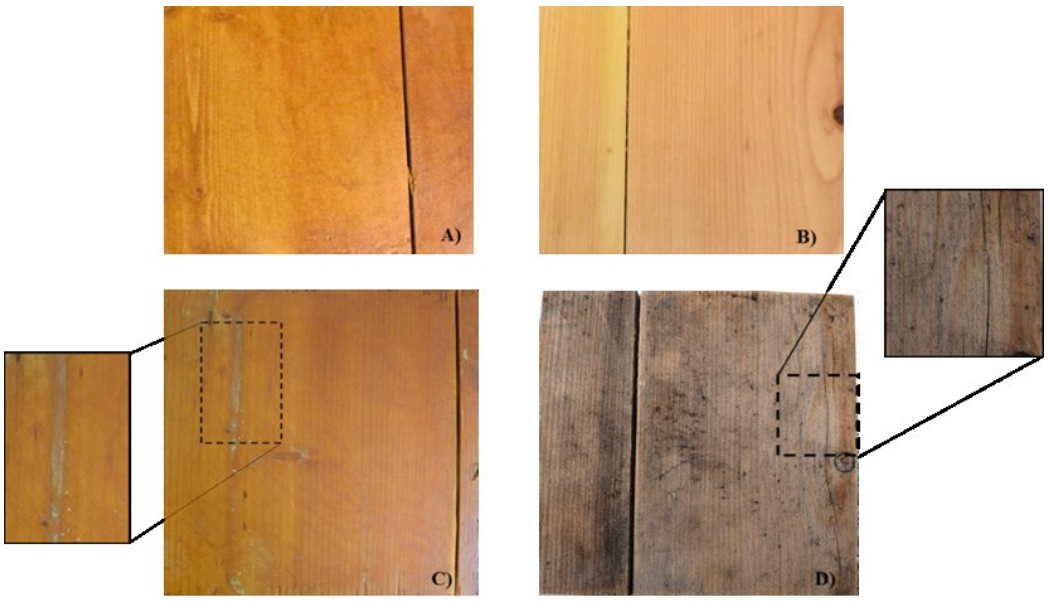

Figure 3.4 Erosion and chalking evaluation based on photograph reference before exposure. A) and B) are samples before exposure. C) erosion after severe flaking. D) chalking/flaking of coating from surface.

Mold growth was defined as smalls dots or dark patterns built up on the coating surface (Figure 3.5). To evaluate the visual degradation of coatings, samples were photographed every month or after each cycle using a Nikon D3300 digital camera at 24.2 Mpx resolution.

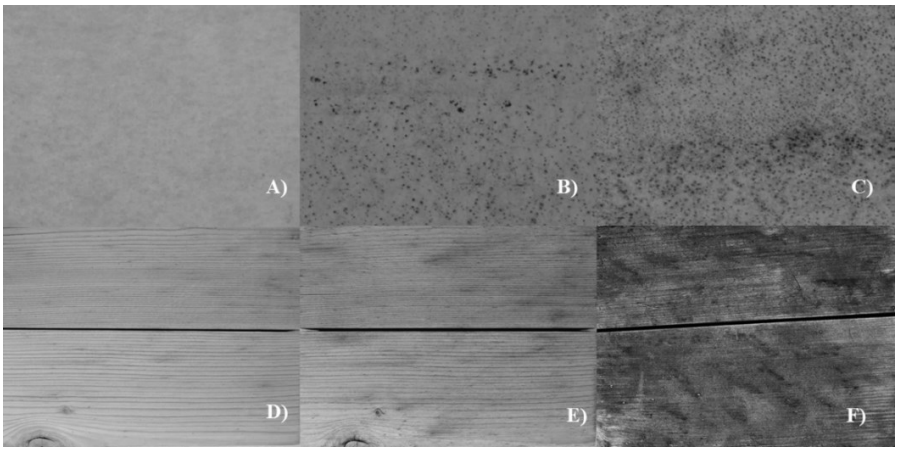

Figure 3.5 Mold growth ranking. A) slight, B) moderate, and C) severe mold reference pictures from the ASTM D3274-09 standard. D), E), and F) slight, moderate, severe mildew respectively.

3.2.3 Color and gloss measurements

The color parameters of the tested blocks were measured using a hand-held spectrophotometer (CM-2300d, Konica Minolta, Osaka, Japan). Both natural and artificially weathered samples were evaluated, and measurements were taken at the same location of the specimens following the Commmission International de l'Eclairage (ISO/CIE, 2019) colorimetry method using color parameters *(L*a*b*)*. Where L^* represents lightness from 0 (black) to 100 (white), a^* chromaticity coordinate red (+) or green (-), and b^* chromaticity coordinate yellow (+) or blue (-).

Five measurements were made per sample exposed to either natural or artificial weathering for each interval. The color changes (ΔL^*, Δa^*, Δb^*) between the exposed period and initial state were determined. Color differences were calculated using Equation 3.5.

$$\Delta E^* = \sqrt{\Delta L^{*2} + \Delta a^{*2} + \Delta b^{*2}} \quad (3.5)$$

The surface luster of samples was measured using a glossmeter ETB-0686 following ISO 2813. Three measurements were made on each sample at a 60° angle every month for 6 months and before and after each artificial weathering test (Figure 3.66).

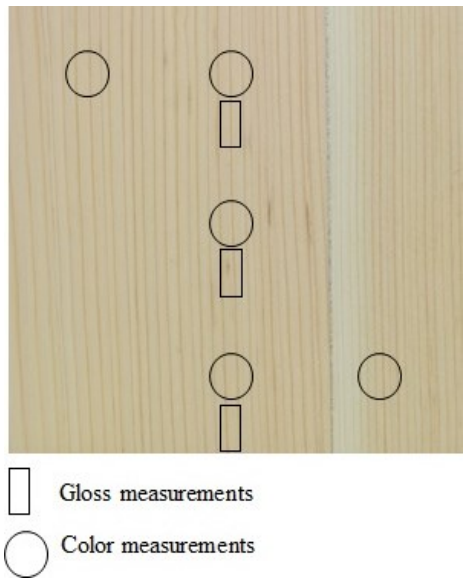

Figure 3.6 Template used to ensure same location of color measurements on samples at each exposure interval.

The alterations of the surface luster of coated and uncoated samples were assessed at the end of each month or artificial weathering cycle. Results were based on a specular gloss value of 96 gloss units (GU), related to the perfect condition under identical illumination and view conditions of highly polished plane, black glass surface. Although surface luster is measured in GU, the results were displayed in percentage for comparison and better visualization.

3.3 Accelerated mold test

A mold growth test was performed on samples generated from three-ply CLT SYP panel described earlier in section 3.1. For each treatment 5 replicates were used totalizing 30 samples.

The test was performed in Växjö, Sweden and in the Department of Forestry and Wood Technology, Linnaeus University.

The test was conducted in a climate chamber (Memmert HCP 246, Memmert GmbH, Germany) under non-sterile conditions. Temperature and RH in the chamber were monitored throughout the experimental period. Samples of sapwood of pine naturally infected by *Aspergillus* sp., *Rhizopus* sp., and *Penicillium* sp. were used as inocula sources. During 14 days the chamber was kept under 27°C and 95% RH to be infested with spores (Figure 3.7).

Figure 3.7 Naturally infected samples placed at bottom of the chamber

The tested samples were hanged edgewise from the top through aluminum bars spaced with a minimum 10 mm gap between two samples (Figure 3.8).

Figure 3.8 Placement of test samples on the top of chamber.

After 29 days of incubation period, as abundant mold growth was observed on some sample surfaces, 3 edges and 2 flat sides of each sample were evaluated for mold rating. Mold growth was visually rated by naked eye and the degree of mold growth was rated from 0 to 6 (see Table 3.5).

Table 3.5 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 days of exposure in the set conditions (95% RH and 27°C)

3.4 Decay fungi test

Test samples (free of biological damages, knots, resin pockets and other defects) were prepared from three-ply CLT hemlock-fir panels. The test set was designed to determine fungal decay progression. The E10 AWPA (2016) standard is a soil-block test of 12 to 24 weeks of duration to achieve 40% weight loss. Unlike the AWPA soil block test specimens, the large CLT specimens required a more discrete baseline that was determined as 30%. The samples followed the same dimensions described earlier in section 3.1.1. and were arranged in duplicate for each exposure time 8, 12, 18 and 24 weeks. The test was conducted following E10 (AWPA, 2016) with some modifications to ensure the feasibility of the test with CLT pieces.

Three 2 L acrylic containers were filled with 700g of soil and 300ml of water based on water holding capacity test. Two feeder strips measuring 72x20x3 mm^3 (length, width, and height) were added to each set (container + soil+ water). The containers were later autoclaved with aluminum foil on top for 45 minutes while their lids were sterilized with ethanol 70%.

After that *Gloeophyllum trabeum* mycelia were inoculated in each container and were left to grow for 20 days. Once the feeder strips were completely covered by *G. trabeum* mycelia, two CLT samples were introduced to each container. The test was conducted in an incubator at 24°C for 24 weeks. At the end of 8, 12, 18 and 24 weeks the samples were removed from testing, and their weight loss was recorded. Figure 3.9 shows the weight loss progression throughout the test.

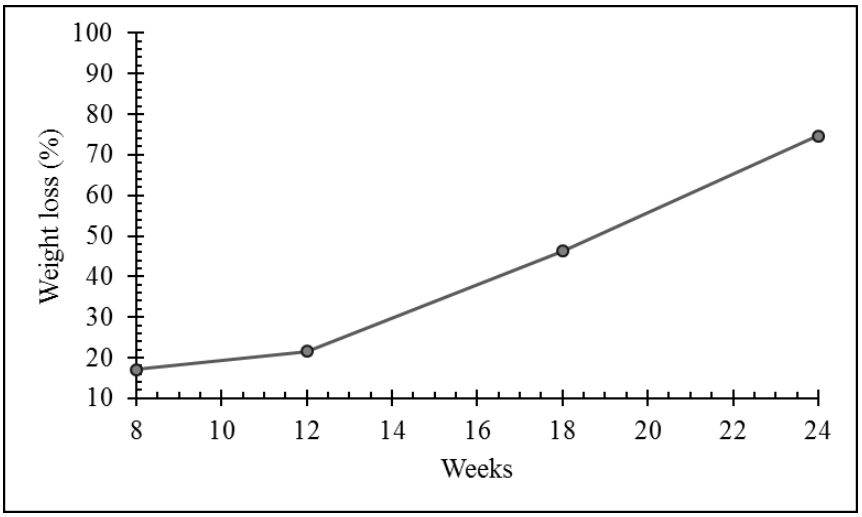

Figure 3.9 Weight loss progression of CLT specimens during 24 weeks of soil block test.

Based on the CLT weight loss progression, another soil block test was performed to evaluate the coatings resistance to *G. trabeum* attack after 18 weeks of test. 36 samples of CLT were prepared, of which 30 were coated and 6 uncoated. The test followed the same procedures mentioned earlier in page 40. The samples were later examined according to visual evidence of decay and weight loss (g).

3.5 Statistical analysis

Statistical Analysis of Variance (ANOVA) were performed for each response variable. The MEE, weight loss by *G. trabeum,* color and gloss changes during artificial weathering were analyzed as completely randomized design based on coating effect. The moisture related properties WRE and ASE were examined based on two factors, coating type (A) and soaking time (B). When the interaction between factors was not significant, each factor was analyzed in isolation.

The color and gloss differences caused by natural weathering were evaluated as split plot design in time described in the statistical model below (Equation 3.6).

$$Y_{ijkl} = \mu + \alpha_i + \delta_k + (\alpha\delta)_{ik} + \varepsilon_{l(ik)} + \beta_j + (\alpha\beta)_{ij} + e_{ijkl} \quad (3.6)$$

Assuming that

$\delta_k \sim N(0, \sigma_\delta^2)$, independently identic distributed (i. i. d.); $(\alpha\delta)_{ik} \sim N(0, \sigma_{\alpha\delta}^2)$; $\varepsilon_{l(ik)} \sim N(0, \sigma_\varepsilon^2)$; $e_{ijkl} \sim N(0, \sigma^2)$.

Where:

μ = overall mean; α_i= coating; δ_k= location (block); $\alpha\delta_{ik}$ = coating*location; $\varepsilon_{l(ik)}$= replicate*coating*location; β_j = time; $\alpha\beta_{ij}$ = interaction between coating and time; e_{ijkl}= experimental error; $_i$ = number of coating treatments, i=1, 2, 3, ...,7; $_j$ = number of time intervals, j=1, 2, 3, …,6; $_k$ = number of locations, k=1, 2; $_l$ = number of reps, l=1, 2, 3, …, 6.

Test was performed at α =0.05, when the sources of variations were detected as significant by Fisher-test ($p \leq 0.05$). Analyses were performed using Statistical Analysis System (SAS) software version 9.4 in PROC MIXED statement (SAS Institute Inc., 2012).

CHAPTER IV

RESULTS AND DISCUSSION

4.1 Preliminary test

The moisture exclusion efficiency (MEE) on coating I was substantially higher than the other coatings, i.e. coating I was more hydrophobic which prevented moisture trapping the coating surface (Table 4.1). This characteristic is important in places where coated wood is not directly exposed to water but is in contact with high relative humidity. In that case, coating I would likely promote moisture protection in damp buildings. In fact, Schmidt and Riggio (2019) pointed out that moisture management is crucial in the serviceability and preservation of buildings.

Table 4.1 Moisture-related properties of coated CLT at 66% RH and 24°C. Means followed by the same letter per column and coating are not significantly different by the t-test (LSD) at α=0.05. Average water repellency efficiency and anti-swelling efficiency during 72 hours soaking.

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

The interaction between time and treatment for WRE was statistically significant at 5% level by the t- Test ($p<0.05$) for short time exposure (0). As the test progressed, soaking times and, water repellency efficiency slightly decreased in the first few hours except in coatings G and H (water uptake higher than untreated samples) (Figure 4.1). Water repellency measures the coatings ability to decrease water absorption. Moisture exclusion is based on retarding transmission of water vapor (Williams 1999).

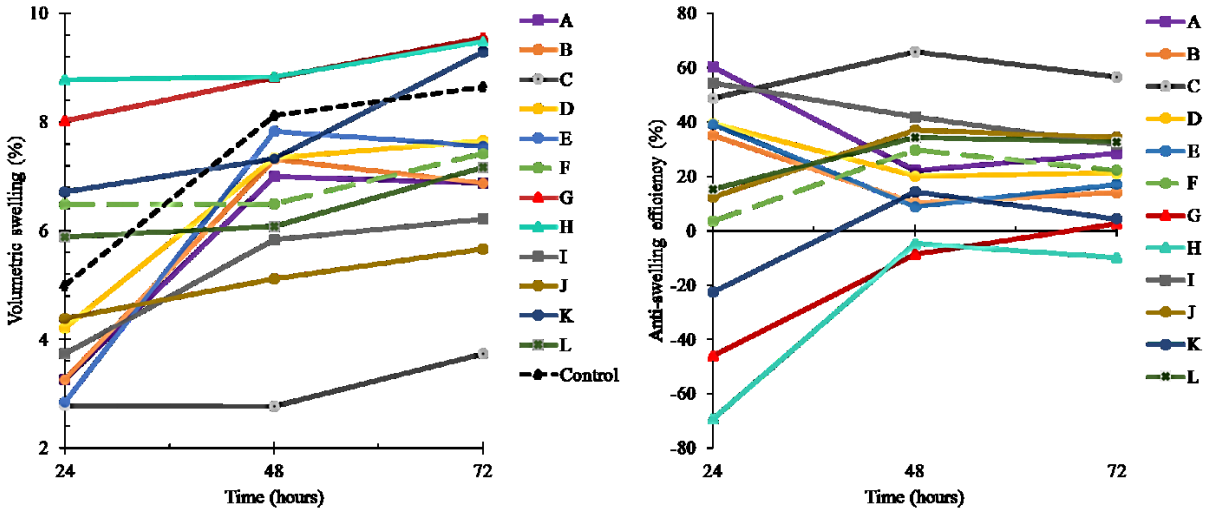

Figure 4.1 Volumetric swelling during 72 hours of water-soaking and water repellency during 2 hours of water-soaking and. Note that coating G was not included on the water repellency graph.

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 higher in coating C followed by I, L, J, F, D, and K. As the interaction between time and coating was not significant ($\alpha=0.05$) for long term water repellency test (0), the main effect coating was analyzed as an isolated factor.

Coating C provided the highest WRE, followed by I, L and J. The CLT samples were mainly composed of end grain that was in contact with water for 72 hours. Consequently, the satisfactory performance of these coatings is related to their ability to fill the voids present in wood cells. Coatings C, I and J are water-repellents composed of nonpolar molecules that might have reduced the rate of water absorption and enhanced dimensional stability (Evans et. al. 2016).

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

The moisture-related properties of coated CLT were performed to determine the durability of coating before exposing them to natural, artificial weathering and fungal attack. Based on the results, coatings C, I, J, F and A were selected for further testing.

4.2 Natural weathering

4.2.1 Visual assessments

Coating type and wood surface variability had an impact on the performance of the wood/coating system. Weathering performance was visibly influenced by exposure site. During the six months of exposure, mainly aesthetic changes were found for water and oil-based coatings. Opaque coatings such as coating A and J were affected the most by outdoor exposure.

ASTM standards for exterior wood coatings performance determine the weathering degradation of coating systems based on blistering, cracking, checking, flaking, chalking, algal

or fungal growth, and surface erosion. Since there was no visual evidence of cracking, checking and blistering on the surface of the tested coatings, the samples were evaluated according to fungal growth, chalking or flaking, and erosion. Table 4.2 displays the visual ratings of samples over time.

Table 4.2 Average rating for the coatings during 6 months of exposure in Starkville and Madison

Coatings	**Starkville**						**Madison**					
	Mold growth											
	Jul	Aug	Sept	Oct	Nov	Dec	Jul	Aug	Sept	Oct	Nov	Dec
A	8	6	4	3	3	3	9	8	7	5	6	5
C	10	10	9	9	9	9	10	10	10	9	9	10
F	10	10	7	7	5	5	10	10	10	9	8	8
I	10	10	7	7	5	5	10	9	7	5	4	6
J	4	2	1	1	1	1	9	5	6	3	3	4
Control	7	5	5	5	4	5	7	5	7	7	6	7
	Chalking and/or Flaking*											
	Jul	Aug	Sept	Oct	Nov	Dec	Jul	Aug	Sept	Oct	Nov	Dec
A	8	8	8	6	4	2	10	10	6	8	10	8
C	10	10	10	10	10	10	10	10	10	10	10	10
F	10	10	10	10	10	10	10	10	8	8	8	10
I	9	8	9	8	6	8	10	9	8	9	8	8
J	6	8	6	8	4	6	8	9	6	8	10	8
Control												
	Erosion*											
	Jul	Aug	Sept	Oct	Nov	Dec	Jul	Aug	Sept	Oct	Nov	Dec
A	10	10	8	6	4	2	10	8	4	4	4	4
C	10	10	10	10	10	10	10	10	10	10	10	10
F	10	10	10	10	10	10	10	10	10	10	10	10
I	8	8	8	8	8	8	10	8	8	8	8	6
J	10	8	6	6	6	6	10	8	6	6	6	6
Control												

*Not applicable for uncoated samples

Overall coating C was the most resistant to fungal growth and subsequent discoloration over time. In either location, coatings F and I were effective in protecting the samples against mildew in the first two months of exposure. Exposure site affected the performance of all treatments. While in Starkville during September all treatments visually presented some type of fungal discoloration, in Madison the same effect was apparent only a month later.

Additionally, whereas in Starkville there was a trend of increased mold growth over time, in Madison fungal growth did not show a pattern. Coatings A and J had a noticeable poorer performance in Starkville because of weathering conditions that increased degradation rate. For instance, coating J specimens had almost complete fungal coverage in September and in the following months (Figure 4.2).

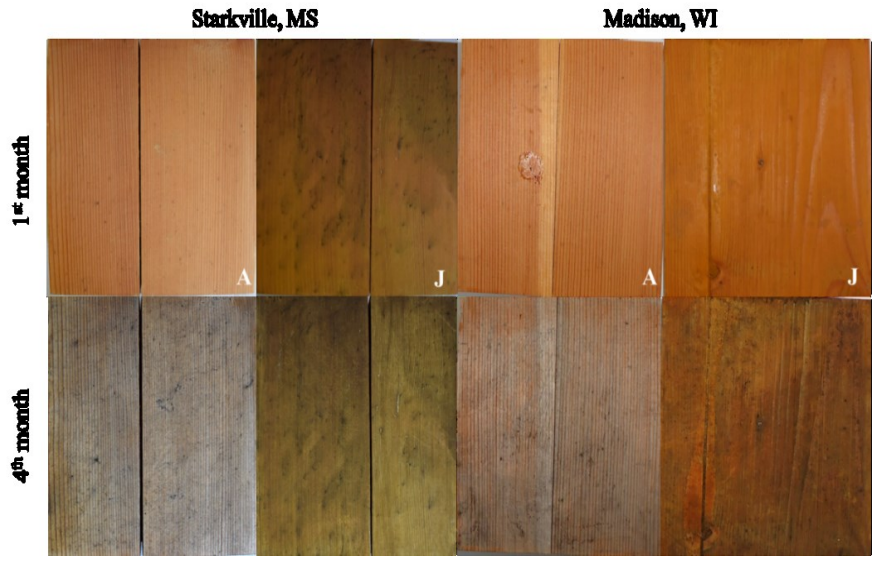

Figure 4.2 Appearance of coatings A and J after four months of outdoor exposure.

The pattern of fungal growth presented on coatings and wood surface was either described as spot growth or non-uniform spread, and complete coverage was only found on

coating J. Coatings A and J were fairly eroded over time once they did not promote enough protection and seemed to contribute to water-trapping between coating and substrate. Both coating did not have any biocide in their composition that would restrain the development of fungus. In addition, Stirling (2011) pointed out that semitransparent wood coatings (e.g. coating J) frequently present signs of early discoloration caused by “black stain” fungi. In Figure 4.3 and Figure 4.4, the surface degradation over time is displayed.

Figure 4.3 Visual changes of uncoated and coated CLT samples after 6 months of natural weathering in Starkville, MS

An efficient coating promotes enough coverage to hide the wood surface from weathering and biological agents. Feist and Hon (1984) pointed out that fungal growth occurs on both wood and coatings surface because the ecological requirements for their development are ordinary, the essential condition for mildew growth is sporadic supply of bulk water. To this end, the ability of coating C to prevent water intrusion may have limited early fungal growth (Figure 4.4). One of the reasons for the superior performance of coatings C and F is likely the inclusion of anti-microbial ingredients presents in their composition. For instance, Coating C is composed of two antimicrobial agents (n-n diethylethanamine "DMEA" and 3-iodo-2 propynyl butyl carbamate "IPBC") while coating F only contains m IPBC. As temperature increases, IPBC may degrade or evaporate (Schultz et al. 2008). For that reason, it is possible that the samples exposed in Starkville coated with F started showing spotted mold growth as early as September.

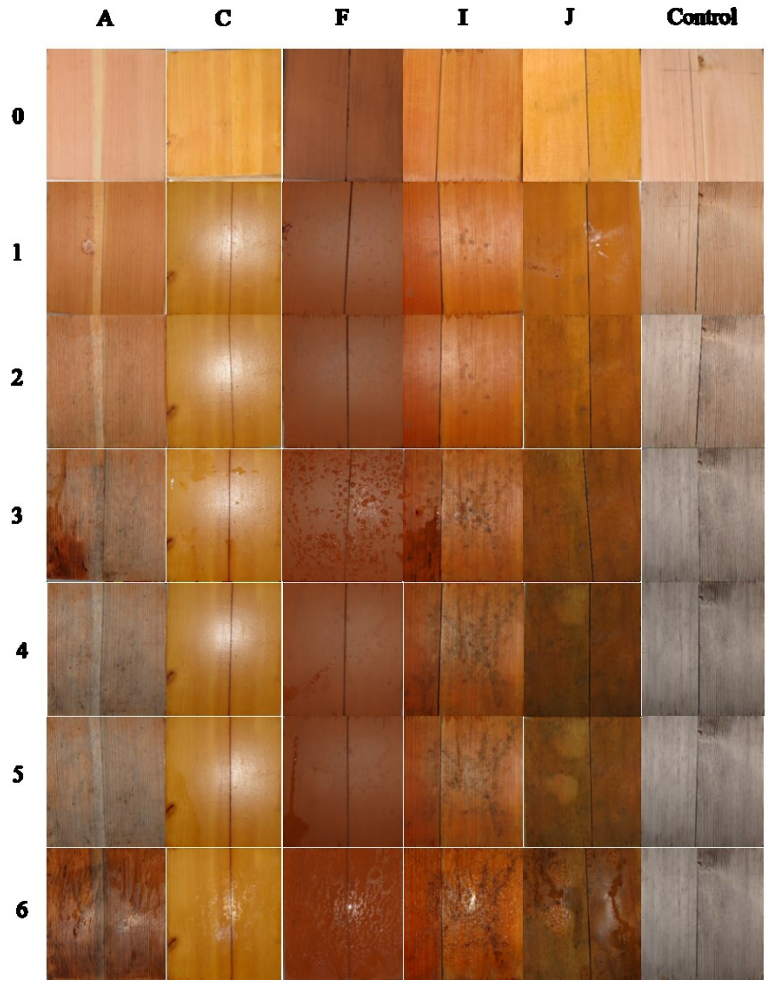

Figure 4.4 Visual changes of uncoated and coated CLT samples after 6 months of natural weathering in Madison, WI.

The performance of coatings was ranked by means of chalking and/or flaking and surface erosion during 6 months of exposure. Visual evaluation of coatings may be highly subjective and even weather dependable. Moisture, rain, snow and wind may remove the chalk from the samples surface affecting the test procedure. Among all the tested finishes, coating C obtained the best results with no visible sign of failure. Coatings F, I, A and J rates varied due to location and time. While coating F had no visual signs of failure when exposed in Starkville, though it did

show slight chalking in Madison (Sept and Oct). Coating I also showed slight flaking in both exposure locations. In Starkville, coating A had the poorest chalking performance, followed by J. Roux et al. (1988) pointed out that penetrating coatings are more likely to fail in a short period of outdoor exposure.

In this work, we found high surface variability of coatings on CLT samples due to percentage of early and latewood, end joints, resin pockets and knots. According to Richter et al. (1995), dimensional stability, surface roughness, wood anatomy and wood density impact the wood-coating interface. Even though, there was an effort to minimize variation through randomization, CLT samples with higher percentage of latewood showed higher coating failure. Cell walls are more likely to swell and shrink than thinner earlywood cell walls (van den Bulcke et al. 2006). This creates stresses such as breaking adhesion between coating and wood, and formation of checks and cracks, which explains why coatings fail first on the latewood then progress into earlywood.

As photodegradation progressed, coatings failed, and the wood surface was left unprotected. Among all the evaluated coatings, only coatings C and F did not show surface erosion during 6 months of exposure. Penetrating coatings such as, A and J, visually eroded after 3 months of exposure, whereas film forming coatings did not. Similar results were reported by Wozniak et al. (1988) who found generally poor performance of penetrating stains due to surface erosion after 2 years of outdoor exposure. Evans (2008) associated coating failure to photo-degradation of lignin at the interface between coating and wood surface.

4.2.2 Color and gloss change

The color parameters (ΔE*, ΔL*, Δa*, and Δb*) and gloss variation (ΔG) were evaluated only based on type of coating and duration of exposure (1, 3, and 5 months of weathering). As experimental units (CLT samples) were randomly assigned to each block (Starkville or Madison), the performance of coating cannot be compared between blocks. In this case, location acted as block.

The results of outdoor exposure obtained from CIE L*a*b* system is displayed on Figure 4.5. After a month (July) of exposure, there was no significant change in lightness (ΔL*) or chromaticity (Δa* and Δb*) of exposed samples. Photodegradation was registered in September and progressed to the end of the data collection.

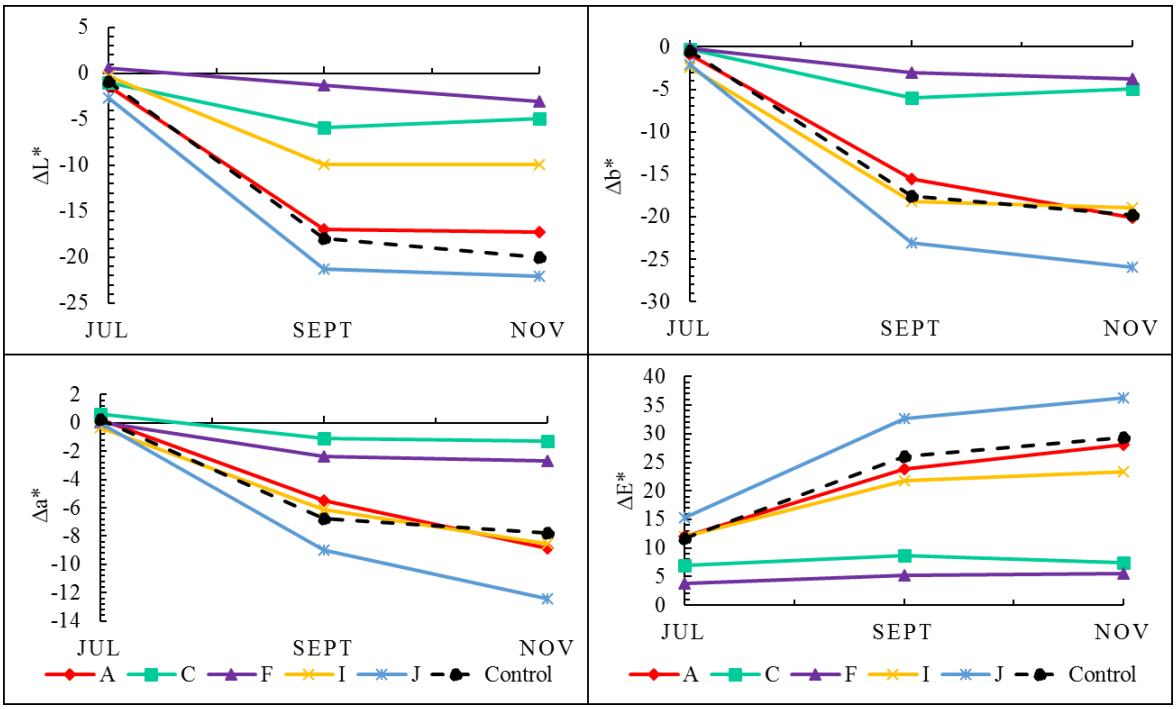

Figure 4.5 Evolution of color change based on time of exposure. ΔL* lightness variation, Δa* red to green variation, Δb* yellow to blue variation and ΔE color difference.

Time of exposure had a significant impact on the magnitude of lightness (ΔL*) degradation. Coatings F and C were significantly the most resistant to darkening after five months of exposure (Table B.1). Coatings J and A were more susceptible to darkening (-ΔL*) over time with no significant difference from uncoated samples. While samples coated with coating J were almost completely covered with mold, coating A was rapidly eroded. The lack of surface protection decreased lightness, which indicates that lignin molecules were likely degraded into quinones by a combination of UV light, oxygen and water (Nzokou et al. 2011).

In terms of chromaticity (characterization of color in red, yellow, green and blue, regardless lightness), coating C and F were less susceptible to greening and bluing over time. The lowest values of Δa and Δb were found for coating J after 3 and 5 months of outdoor exposure. Although coating J and F are opaque semi-transparent, they differ in composition. The alkyd solvent of coating J is more likely to degrade with repetitive cycles of water and UV exposure, which contributes to coating erosion and surface roughness (Builian and Graystone 2009).

Overall, coating J was statistically the least stable (Figure 4.5– see the highest ΔE*). As expected, coating F (semi-transparent film-forming) achieved the lowest ΔE. Wood products coated with the semitransparent acrylic are reported to have better performance against photodegradation, as their pigment restricts transmittance of UV light to the wood surface (Ozgenc et al. 2012; Schaller and Rogez 2007; Allen et al. 2002). Even though literature reports low photodegradation resistance of clear coatings, coating C was the second most color stable.

The interaction between time of exposure and coating was statistically significant ($p<0.05$) for gloss change. Initial gloss of samples before installation varied between 2 to 25 GU,

which is considered very low, due to both wood surface variation and coating type. Overall, the outdoor exposure did not affect the gloss of coating A and uncoated samples (Figure 4.6).

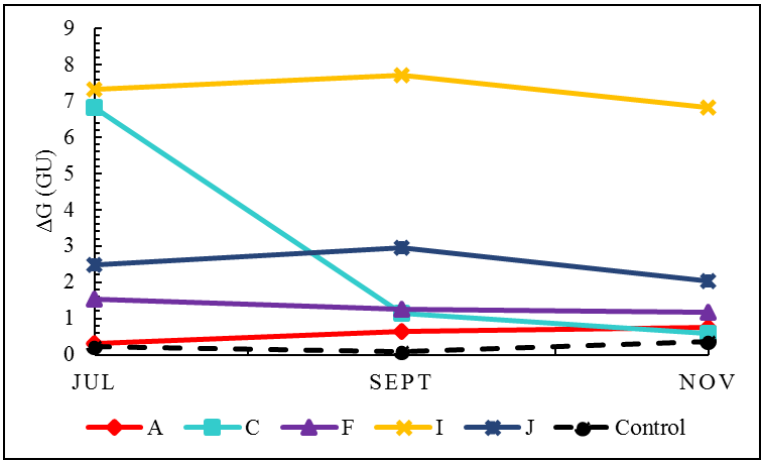

Figure 4.6 Gloss variation (GU) of tested coatings exposed to natural weathering.

Coating I was the least resistant to gloss change. Wood et al. (2000) pointed out that loss of gloss is an indicator of initial degradation and is caused by either non-chemical changes (e.g. cracking, checking), or to chemical changes located on top fraction of the coating. Since some coatings had very low gloss values before exposure due to its opaque nature (e.g. coating J), alterations on their surface luster was not detected.

4.2.3 Water uptake

The interaction between coating type and time of exposure for water uptake was not significant at 5% level (Table B.6). When evaluated without effect of time, water uptake did not differ significantly among coating types. Although, there was an effort to minimize the variation

caused by locations by randomizing the samples within location and coating type, the ANOVA test showed that location had a significant impact on the results as displayed in Figure 4.7

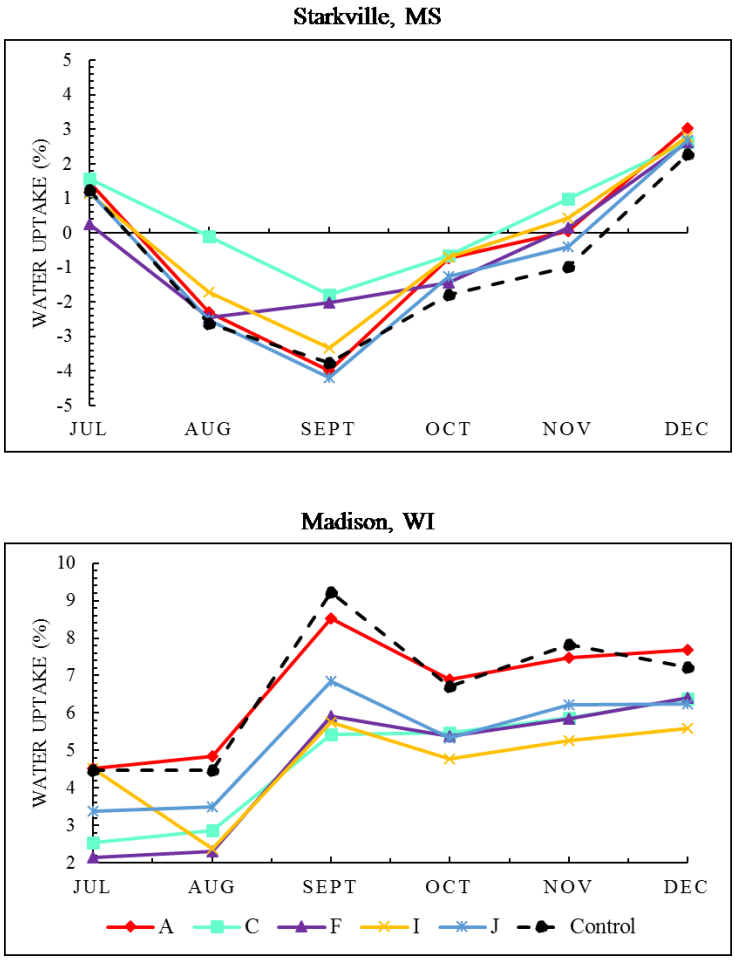

Figure 4.7 Water uptake of uncoated and coated samples exposed to six months natural weathering.

The differences in water uptake of samples exposed in one place to the other were closely related to weathering factors such as temperature, precipitation and radiation. The water uptake for samples exposed in Madison was higher (Table 3.3). Low temperatures were reported in the site, along with snow and ice. According to Berdahl et al. (2008) freeze-thaw cycles are

environmental stresses that may cause cracks on surface material due to expansion and contraction.

Even though the precipitation in Starkville was higher, the intense radiation and temperature resulted in lower water uptake. Differences in temperature cause stress to any material due to gradients of thermal expansion (Berdahl et al. 2008). Moreover, the result of repetitive cycles of wetting and drying cause alteration of chemical bonds and oxidation (Joshi and Pagni 1994).

Water uptake in CLT during service brings concerns on dimensional stability and durability. Polyurethanes are the most common adhesive in CLT production because of its considerable resistance to water and fire (Wang et al. 2018). However, combinations of liquid water, shrinking and swelling tend to break chemical bonds between wood and adhesive, resulting in CLT delamination. High moisture content also contributes to mold and decay development.

4.3 Artificial weathering

4.3.1 Visual appearance

The transparent and semi-transparent coatings had different performance during artificial exposure. The coatings A, J and I presented some type of chalking that occasionally could result in surface erosion. It is important to mention that some studies describe degradation of clear coating as cracking or flaking. The type of degradation found for the opaque coatings used in this study (A and J) were best described as chalking due to their powdery appearance (Figure 4.8).

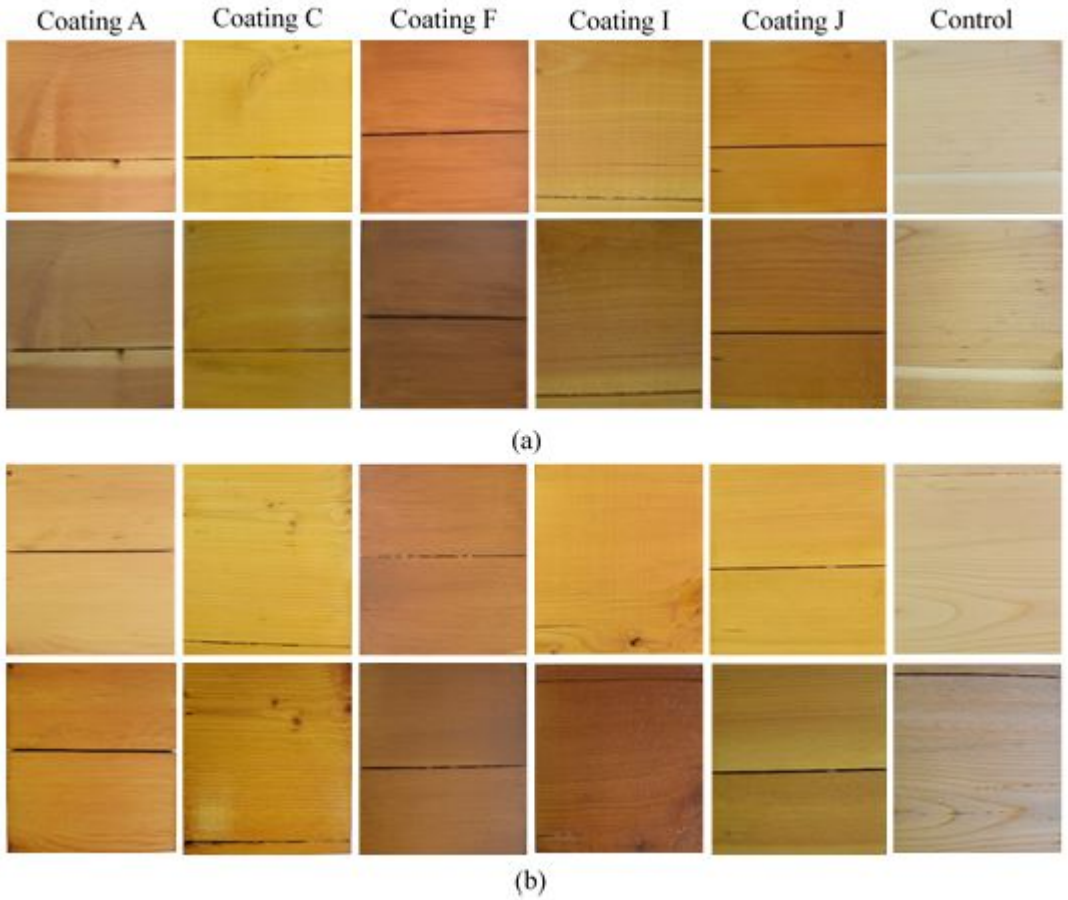

Figure 4.8 Surface change of selected tested samples. First and second rows correspond to before and after exposure, respectively. (a) after 360 hours of exposure and (b) after 1800 hours of exposure.

Although the short-term exposure resulted in no major visual change on most of the treatments, coating I exhibited decrease in brightness with some type of bleaching. Grigsby and Steward (2018) found similar results on commercial coatings after 1000h of accelerated weathering. The long exposure of 1800h resulted in slight chalking of coating A and J, and moderate chalking of coating I.

4.3.2 Color and gloss changes

Color changes of coated and uncoated CLT samples exposed for 360h and 1800h are summarized in Table 4.3. Although, short-term exposure of 360 h showed discrete changes, there was statistical difference between treatments at the level of 5% significance. Overall, coatings did not express great lightness degradation in the first accelerated weathering test except for coating J (ΔL*=-4.8 units). The lowest value of ΔL* was reported for untreated samples (-10.4 units) that became darker after test. This result was expected because wood chemical components, such as extractives rapidly, degrade with photo radiation exposure leaving them darker (Feist 1990).

Table 4.3 Color change values of artificial weathered CLT samples (Standard deviation)

	360 h				1800 h			
Coating	CIE Lab coordinates							
	*ΔL**	*Δa**	*Δb**	*ΔE**	*ΔL**	*Δa**	*Δb**	*ΔE**
A	-2.6	-0.9	0.2	2.9	-12.9	3.2	-1.3	13.4
	(1.3)[1]	(0.5)	(0.7)	(1.1)	(1.4)	(0.7)	(0.8)	(1.5)
C	-1.2	0.0	-1.1	1.8	-7.6	3.0	-3.4	8.9
	(0.2)	(0.6)	(0.7)	(0.7)	(1.1)	(0.4)	(0.2)	(1.0)
F	1.5	-0.2	-0.3	1.7	-1.7	-1.3	-1.6	2.9
	(2.2)	(0.2)	(0.3)	(2.1)	(0.4)	(1.3)	(0.3)	(0.8)
I	-1.6	0.3	-3.5	4.2	-11	-0.6	-12.6	16.9
	(1.7)	(1.3)	(2.7)	(2.9)	(2.2)	(1.0)	(3.9)	(4.2)
J	-4.8	-0.4	-2.4	5.5	-12	0.7	-6.7	13.9
	(0.5)	(1.0)	(0.4)	(0.4)	(0.6)	(1.7)	(1.9)	(0.4)
Control	-10.4	2.0	7.3	13	-11.3	-0.8	-5.5	12.6
	(0.8)	(1.0)	(1.8)	(1.8)	(0.2)	(0.6)	(1.9)	(0.9)

Chromaticity of coatings was not susceptible to degradation in short-term exposure. The highest change for coated wood was found on coating I (Δb*= -3.5 units). Uncoated samples however, were highly sensitive to increase in yellowness after short-term exposure (Δb*= 7.3).

The overall color change promoted by artificial weathering is expressed as ΔE*. Samples coated with either coating I or J were less color stable. The acrylic water-based coatings C and F had a better performance at the beginning of the test. The trend associated with resistance to color change was C > F > A > I > J > Control.

The color changes after 1800h of artificial weathering were statistically different among treatments (α=0.05). Long-term exposure resulted in low resistance to darkening of coated and uncoated samples. The alkyd-based coatings A, J, I showed high sensitivity to light degradation (ΔL*=-12.9, ΔL=-12.0, ΔL*=11.0 respectively). According to Williams (2005) alkyd-based coatings are not able to protect oil and resin of wood surface from light degradation. In addition, the lightness sensitivity found for these coatings was not statistically different from uncoated samples (Table D.1).

Overall, coatings did not show instability to changes in the Δa* spectrum. The highest values were found for coatings A and C (Δa*=3.23 and ΔL=3.0 respectively). The major change in Δb* was measured on coating I (-12.6 units) followed by coating J and control samples (-6.7 and 5.5 respectively). The higher color change after 1800h of accelerated weathering may be related to the degradation of the protective coatings and the leaching of wood surface components (extractives and lignin). Coating F was the most color stable treatment which is consistent with the results of other research (Panek et al. 2018; Evans 2015; Grull et al. 2011) that found pigmented coatings more resistant to photo-degradation than clear coatings.

The gloss of coated and uncoated CLT significantly changed after exposure. Based on the initial surface luster of the samples, the oil-based coatings were affected more after exposure than water-based coatings for either exposure time (Table 4.4). Oil and alkyd finishes are less

permeable and are more likely to break as time progresses (Builian and Graystone 2009). If the coating is transparent, they are even more fragile and sensitive to UV-degradation.

Table 4.4 Gloss change of coated and uncoated CLT after 360h and 1800h of artificial weathering. ΔG is expressed in gloss units (GU). (Standard deviation).

Treatment	ΔG_{360}	Gloss change (%)	ΔG_{1800}	Gloss change (%)
A	-0.5 (0.4)	20.5	-0.7 (0.1)	33.9
C	0.2 (0.4)	1.7	4.2 (0.9)	17.9
F	-0.3 (0.2)	9.9	-0.2 (0.4)	9.4
I	-0.9 (0.7)	30.7	-0.9 (0.8)	40.7
J	-0.9 (0.7)	45.6	-1.2 (0.2)	63.9
Control	-0.8 (0.3)	39.5	1.0 (0.5)	54.7

Similar results were found by Pánek et al (2017), who reported gloss degradation on an oil-based coating after 3 weeks of artificial weathering exposure. The loss of gloss indicates that degradation is occurring due to non-chemical changes (surface wrinkling) or chemical changes located in the top fraction of the coating (Wood et. al. 2000).

4.4 Mold growth

After 29 days of exposure to fungal spores, the highest mold growth was observed on control (pine) samples. Coating C performed best with no visible mold growth (Table 2 and Figure 4). Even though, Coating J samples showed small, spare amount of mold, when compared to other treatments it had the worst performance during test.

Table 4.5 Average mold grades (±standard deviation) on different test samples

Test sample	Mold grade
A	0.4±0.38
C	0.0±0.00
F	0.1±0.18
I	0.5±0.50
J	1.4±0.36
Control (CLT)	2.5±0.18
Control (pine)	6.0±0.00

Both coating C and F have IPBC in their composition, i.e., they have anti-microbial action that likely prevented mold infection. Although the test ran for only 29 days, the results are highly consistent with the performance of these coatings when tested outdoors (see section 4.2.1). Products with a lower score in mold testing (Coatings C and F) would likely perform better in service.

4.5 Fungal weight loss

Coating treatments had a significant impact on the weight loss of CLT samples from fungal growth (Table E.1). The weight loss of coatings F and J samples was not statistically different from uncoated samples (Figure 4.9). Both coatings were not able to protect CLT from *G. trabeum* degradation. In the case of coating F, its high permeability may actually facilitate water absorption that led to optimal conditions for fungal development. Coating J is an alkyd-based product that is liable to trap water through end-grain (Viitanen et. al. 2010).

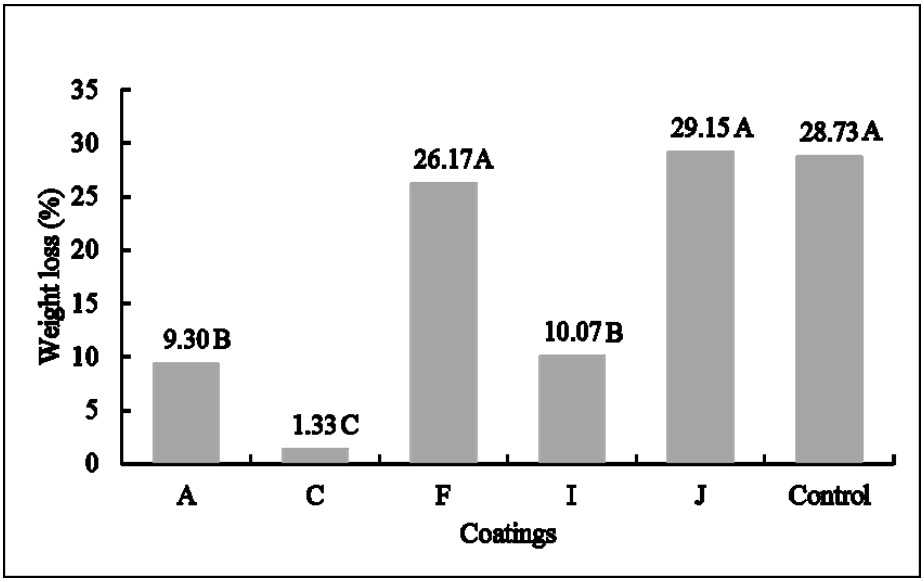

Figure 4.9 Weight loss tested CLT samples exposed to *G. trabeum* during 18 weeks. Means with the same letter are not significantly different.

The lower weight loss values were found on samples finished with coating C followed by A and I. Coating C's hydrophobic nature prevented water intrusion, which most likely protected the samples against fungal colonization (Figure 4.10). Paints and coatings are unlikely to protect wood materials against decay. De Meijer (2001) explains that the influence of coatings on fungal degradation is primarily through their influence in wood-moisture content. However, if a coating is not able to exclude moisture, it might promote decay due to a low drying rate.

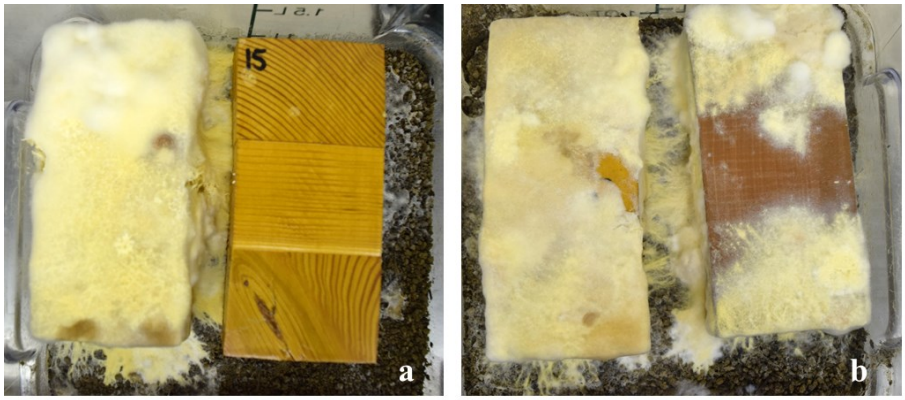

Figure 4.10 Fungal growth on CLT samples: a) Left: coating J, right: coating C. b) Left: coating J, right: coating F.

The ability that coating C showed in preventing decay in CLT exposed to a harsh condition (direct soil contact, high humidity, aggressive decay fungi) is of high importance, as CLT rapidly absorbs water (specifically from end-grain) and may be exposed to rain, high humidity and changes in temperature during transport, storage and construction. Currently, industrial CLT panels (heavy equipment mats) available in the market are intended to be used in similar harsh conditions. Hydrophobic coatings such as those tested successfully here may be a temporary solution for short-term exposure of this type CLT panels (Figure 4.11).

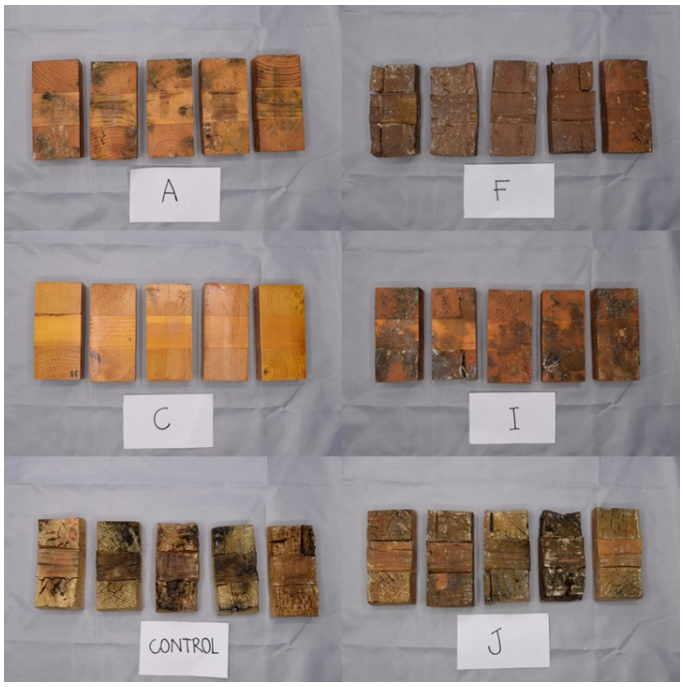

Figure 4.11 Appearance of CLT samples after 18 weeks of exposure to *G. trabeum* in soil block test.

It is important to point out that coatings are not intended to protect wood from decay. Coatings are primarily used to protect wood from water, UV-light, blue-stain and mold degradation. The most likely reason for coating C to have an excellent performance in this test is because of the biocides present in its composition. Furthermore, to protect wood from decay fungi, it is necessary to implement other protective methods such as pressure treatment and surface treatments paired with biocides.

Cappellazzi et al (2020) describe the dimensional constraints of massive timber thatmake its treatability impractical with current treating cylinders. Lim et al (2020) tested the potential for manufacturing CLT from southern yellow pine (SYP) lumber treated prior to layup with micronized copper azole, using various adhesives to bind the treated laminate layers. Lim et al. concluded that CLT panels glued with polyurethane have an overall better performance than

untreated CLT manufactured in the current method (2020). Therefore, when CLT is exposed outdoor above ground or in ground contact it is possible, and likely necessary, to utilize treated products.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

This study investigated the performance of exterior wood coatings exposed to abiotic and biotic factors. Variables such as moisture exclusion, water repellency, volumetric swelling and anti-swelling efficiency were measured to determine the ability of coating to prevent water uptake and consequent swelling. 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. Coatings C and I promoted high water repellency on CLT, and the latter is the most effective in moisture exclusion. Either one would be a reasonable solution for short-term exposure during transport, storage or construction.

The top five coatings selected in the preliminary study were applied on CLT samples then exposed to natural (Starkville-MS and Madison-WI), artificial weathering and brown rot fungus (*G. trabeum*). The visual rakings and color change results reported on the samples exposed outdoor were highly consistent. In either location, coatings C and F were the most durable treatments on visual assessments and color change parameters. One reasons for the superior performance of coatings C and F is likely the inclusion of anti-microbial ingredients in their composition. The poor performance of coatings A and J was observed to coincide with increased

mold growth, chalking, erosion and color change over other treated samples. Gloss did change over time, specifically for coatings I and C, while other variations were not reported due to low values in the beginning of the exposure. Water uptake is a sensitive variable that is influenced by substrate variation (defects, type of grain, earlywood and latewood and end-joint) and climatic conditions. For these reasons, the effect of coatings on water uptake was not significant. Combinations of water, temperature, and radiation impacted the coatings performance. Even when surface the surface is protected, variations in the CLT panels such as end-joint, cracks, checks can facilitate water uptake that eventually will result in coating failure, delamination and fungal attack.

Artificial weathering performed in short-term was intended to be more intense than the outdoor exposure, and the visual appearance and color change of samples exposed to artificial weathering had some similarities with the samples exposed outdoors. Coatings A, I and J had slight to moderate chalking in long-term exposure. These same coatings were the most sensitive to lightness, color and gloss change. Therefore, an artificial weathering test of 1800h or greater may screen potential durable coatings for CLT. However, it is important to consider that in artificial weathering tests biological agents such as fungi and bacteria are not present. As biological factors are added the service life of coatings will be diminished.

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 fungal development. Coating C was found to be the best protection against weight loss caused by *G. trabeum*. Both biocides and the physical barrier created by the film-forming nature of coating C protected the CLT samples from decay.

Finishes alone are not able to protect CLT during shipping, construction, manufacturing or during service life. As soon as CLT components are exposed to water and other weathering factors, finishes start to fail, because mass timber panels have a unique geometry, which impairs performance when exposed to biotic and abiotic factors. Penetrating coatings, for instance are not able to promote sufficient protection against water and fungal infestation. Therefore, to maintain the integrity of CLT buildings and structures, coatings need to be formulated to promote both physical and chemical protection for end-grain portions of the material. Surface treatments combined with biocides may be an adequate treatment that can be implemented in the CLT industry to increase durability of buildings and public safety. Ultimately, new coating formulations should aim to protect the end-grain of such composite products, even though currently available coatings are a stop-gap protectant for CLT against potential weathering damage.

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APPENDIX A

ANALISYS OF VARIANCE OF MOISTURE-RELATED PROPERTIES

Table A.1 Moisture exclusion effectiveness (MEE) on coated and uncoated CLT.

Source	DF	Sum of Squares	Mean Square	F-Value	p-value
Coat	11	25060.1	2278.2	117.65	<.0001
Error	48	929.5	19.4		
Corrected Total	59	25989.6			

Table A.2 Water repellency and effectiveness (WRE) on coated and uncoated CLT in function of time (0.5, 1, 2, 24, 48 and 72 hours).

Source	DF	Type III SS	Mean Square	F-Value	p-value
Coat	11	198913.2	18083.0	36.9	<.0001
Time	4	56725.4	14181.3	28.9	<.0001
Coat*Time	44	26122.7	593.7	1.2	0.19

Table A.3 Water repellency effectiveness (WRE) during short water soaking test (0.5, 1 and 2 hours) on coated and uncoated CLT.

Source	DF	Type III SS	Mean Square	F Value	p-value
Coat	2	744.1	372.5	18.9	<.0001
Time	11	96361.7	8760.2	444.4	<.0001
Coat*Time	22	1784.8	81.1	4.1	<.0001

Table A.4 Water repellency effectiveness (WRE) in function of time (24, 48 and 72 hours) on coated and uncoated CLT.

Source	DF	Type III SS	Mean Square	F Value	p-value
Coat	11	89395.1	8126.8	72.5	<.0001
Time	2	2489.5	1244.7	11.1	<.0001
Coat*Time	22	1428.3	64.9	0.6	0.93

Table A.5 Water repellency effectiveness (WRE) on coated and uncoated CLT after 72h of water-soaking.

Source	DF	Sum of Squares	Mean Square	F Value	p-value
Coat	11	41299.3	3754.5	5.58	<.0001
Error	39	26242.6	672.9		
Corrected Total	50	67541.9			

Table A.6 Volumetric swelling on coated and uncoated CLT in function of time (24, 48 and 72h).

Source	DF	Type III SS	Mean Square	F Value	p-value
Coat	12	448.7	37.4	15.1	<.0001
Time	2	204.1	102.0	41.2	<.0001
Coat*Time	24	130.1	5.4	2.2	0.002

APPENDIX B

ANALYSIS OF VARIANCE OF NATURAL WEATHERING RESPONSE VARIABLES

Table B.1 Changes in lightness(ΔL*) of tested samples after 1, 3 and 5 months of weathering exposure.

Type 3 Analysis of Variance							
Source	DF	Sum of Squares	Mean Square	Error Term	Error DF	F Value	p<0.05
Coat	5	4622.53	924.51	MS(a)	53	54.55	<.0001
Time	2	5423.08	2711.54	MS(b)	108	100.5	<.0001
Coat*Time	10	1687.36	168.74	MS(b)	108	6.25	<.0001
Loc (Block)	1	897.09	897.09	MS(a)	53	52.93	<.0001
Rep(Loc*Coat) (a)	53	898.27	16.95	MS(b)	108	0.63	0.9692
Residual (b)	108	2913.89	26.98	.			

Table B.2 Changes in Δa* of tested samples after 1, 3 and 5 months of weathering exposure

Type 3 Analysis of Variance							
Source	DF	Sum of Squares	Mean Square	Error Term	Error DF	F Value	p<0.05
Coat	5	853.06	170.61	MS(a)	53.332	60.92	<.0001
Time	2	1609.79	804.89	MS(b)	106	489.45	<.0001
Coat*Time	10	433.79	43.38	MS(b)	106	26.38	<.0001
Loc (Block)	1	29.14	29.14	MS(a)	53.365	10.41	0.0021
Rep(Loc*Coat) (a)	53	148.75	2.81	MS(b)	106	1.71	0.0101
Residual (b)	106	174.32	1.64	.			

Table B.3 Changes in Δb*of tested samples after 1, 3 and 5 months of weathering exposure

Type 3 Analysis of Variance							
Source	DF	Sum of Squares	Mean Square	Error Term	Error DF	F Value	p<0.05
Coat	5	5076.06	1015.21	MS(a)	53	79.21	<.0001
Time	2	7592.15	3796.07	MS(b)	108	227.24	<.0001
Coat*Time	10	2047.00	204.70	MS(b)	108	12.25	<.0001
Loc (Block)	1	1297.81	1297.81	MS(a)	53	101.26	<.0001
Rep(Loc*Coat) (a)	53	679.28	12.82	MS(b)	108	0.77	0.8574
Residual (b)	108	1804.13	16.70	.			

Table B.4 Color changes (ΔE*) of tested samples after 1, 3 and 5 months of weathering exposure

Type 3 Analysis of Variance							
Source	DF	Sum of Squares	Mean Square	Error Term	Error DF	F Value	p<0.05
Coat	5	12273.00	2454.69	MS(a)	53	170.71	<.0001
Time	2	4456.36	2228.18	MS(b)	108	838.52	<.0001
Coat*Time	10	2018.93	201.89	MS(b)	108	75.98	<.0001
Loc (Block)	1	226.58	226.58	MS(a)	53	15.76	0.0002
Rep(Loc*Coat) (a)	53	762.09	14.38	MS(b)	108	5.41	<.0001
Residual (b)	108	286.99	2.66	.	.	.	.

Table B.5 Gloss changes of tested samples after 1, 3 and 5 months of weathering exposure.

Type 3 Analysis of Variance							
Source	DF	Sum of Squares	Mean Square	Error Term	Error DF	F Value	p<0.05
Coat	5	1004.99	201.00	MS(a)	53	19.77	<.0001
Time	2	43.25	21.62	MS(b)	108	8.14	0.0005
Coat*Time	10	207.08	20.71	MS(b)	108	7.8	<.0001
Loc (Block)	1	158.67	158.67	MS(a)	53	15.6	0.0002
Rep(Loc*Coat) (a)	53	538.92	10.17	MS(b)	108	3.83	<.0001
Residual (b)	108	286.90	2.66	.	.	.	.

Table B.6 Water uptake of tested samples during 6 months of weathering exposure

Type 3 Analysis of Variance							
Source	DF	Sum of Squares	Mean Square	Error Term	Error DF	F Value	p<0.05
Coat	5	51.39	10.28	MS(a)	53.028	0.42	0.8346
Time	5	531.84	106.37	MS(b)	268	29.56	<.0001
Coat*Time	25	49.61	1.98	MS(b)	268	0.55	0.9615
Loc (Block)	1	3588.12	3588.12	MS(a)	53.033	145.76	<.0001
Rep(Loc*Coat) (a)	53	1306.99	24.66	MS(b)	268	6.85	<.0001
Residual (b)	268	964.30	3.60	.	.	.	.

APPENDIX C

LEAST SQUARE MEANS COMPARISONS OF NATURAL WEATHERING VARIABLES

Table C.1 Least square means comparisons of lightness variation (ΔL*) on tested samples after 1, 3 and 5 months of exposure.

COAT	TIME	Estimate	Letter[1] Group
F	Month 1	0.61	A
I	Month 1	-0.29	A
Control	Month 1	-0.93	A
C	Month 1	-1.03	A
A	Month 1	-1.33	A
J	Month 1	-2.61	A
COAT	TIME	Estimate	Letter Group
F	Month 3	-1.32	A
C	Month 3	-5.94	B
I	Month 3	-9.90	B
A	Month 3	-17.00	C
Control	Month 3	-17.94	C
J	Month 3	-21.28	C
COAT	TIME	Estimate	Letter Group
F	Month 5	-3.05	A
C	Month 5	-4.95	A
I	Month 5	-9.91	B
A	Month 5	-17.30	C
Control	Month 5	-20.02	CD
J	Month 5	-22.11	D

[1]Means with the same letter are not significantly different.

Table C.2 Least square means comparisons Δa* variation on tested samples after 1, 3 and 5 months of exposure

COAT	TIME	Estimate	Letter[1] Group
C	Month 1	0.59	A
A	Month 1	0.26	A
Control	Month 1	0.25	A
F	Month 1	0.07	A
J	Month 1	0.00	A
I	Month 1	-0.35	A
COAT	TIME	Estimate	Letter Group
C	Month 3	-1.09	A
F	Month 3	-2.35	A
A	Month 3	-5.47	B
I	Month 3	-6.12	B
Control	Month 3	-6.75	B
J	Month	-9.01	C
COAT	TIME	Estimate	Letter Group
C	Month 5	-1.28	A
F	Month 5	-2.66	B
Control	Month 5	-7.76	C
I	Month 5	-8.53	C
A	Month 5	-8.86	C
J	Month 5	-12.43	D

[1]Means with the same letter are not significantly different.

Table C.3 Least square means comparisons Δb* variation on tested samples after 1, 3 and 5 months of exposure

COAT	TIME	Estimate	Letter[1] Group
F	Month 1	-0.13	A
C	Month 1	-0.25	A
Control	Month 1	-0.51	A
A	Month 1	-0.89	A
J	Month 1	-2.10	A
I	Month 1	-2.42	A
COAT	TIME	Estimate	Letter Group
F	Month 3	-3.08	A
C	Month 3	-6.05	A
A	Month 3	-15.57	B
Control	Month 3	-17.56	B
I	Month 3	-18.23	B
J	Month 3	-23.08	C
COAT	TIME	Estimate	Letter Group
F	Month 5	-3.73	A
C	Month 5	-4.95	A
I	Month 5	-18.94	B
Control	Month 5	-19.82	B
A	Month 5	-20.10	B
J	Month 5	-25.90	C

[1]Means with the same letter are not significantly different.

Table C.4 Least square means comparisons of color change ΔE* on tested samples after 1, 3 and 5 months of exposure.

COAT	TIME	Estimate	Letter[1] Group
J	Month 1	15.25	A
A	Month 1	11.99	B
I	Month 1	11.95	B
Control	Month 1	11.68	B
C	Month 1	6.91	C
F	Month 1	3.75	D
COAT	TIME	Estimate	Letter Group
J	Month 3	32.70	A
Control	Month 3	26.10	B
A	Month 3	23.79	C
I	Month 3	21.82	C
C	Month 3	8.69	D
F	Month 3	5.14	E
COAT	TIME	Estimate	Letter Group
J	Month 5	36.29	A
Control	Month 5	29.31	B
A	Month 5	28.02	B
I	Month 5	23.32	C
C	Month 5	7.35	D
F	Month 5	5.59	D

[1]Means with the same letter are not significantly different.

Table C.5 Least square means comparisons of gloss change ΔG* on tested samples after 1, 3 and 5 months of exposure.

COAT	TIME	Estimate	Letter[1] Group
Control	Month 1	-0.23	A
A	Month 1	-0.32	A
F	Month 1	-1.53	AB
J	Month 1	-2.47	B
C	Month 1	-6.83	C
I	Month 1	-7.31	C
COAT	TIME	Estimate	Letter Group
Control	Month 3	0.08	A
A	Month 3	-0.63	A
C	Month 3	-1.13	AB
F	Month 3	-1.26	AB
J	Month 3	-2.96	B
I	Month	-7.7	C
COAT	TIME	Estimate	Letter Group
Control	Month 5	-0.37	A
C	Month 5	-0.58	A
A	Month 5	-0.74	A
F	Month 5	-1.18	A
J	Month 5	-2.03	A
I	Month 5	-6.83	B

[1]Means with the same letter are not significantly different.

APPENDIX D

ANALYSIS OF VARIANCE AND T-TEST FOR ARTIFICAL WEATHERING VARIABLES

Table D.1 Changes in lightness(ΔL*) of uncoated and coated CLT exposed to 360 hours of artificial weathering

Source	DF	Sum of Squares	Mean Square	F Value	p<0.05
Coat	5	253.79	50.76	28.34	<.0001
Error	12	21.49	1.79		
Corrected Total	17	275.29			

Table D.2 Least significance difference on lightness of uncoated and coated CLT exposed to 360 hours of artificial weathering

Alpha			0.05
Error Degrees of Freedom			12
Error Mean Square			1.79
Critical Value of t			2.18
Least Significant Difference			2.38
t Grouping[1]		**Mean**	**Coat**
	A	1.53	F
	B	-1.17	C
	B		
	B	-1.60	I
	B		
C	B	-2.57	A
C			
C		-4.87	J
	D	-10.43	Control

[1]Means with the same letter are not significantly different.

Table D.3 Changes in Δa* of uncoated and coated CLT exposed to 360 hours of artificial weathering

Source	DF	Sum of Squares	Mean Square	F Value	p<0.05
Coat	5	15.54	3.11	4.18	0.020
Error	12	8.92	0.74		
Corrected Total	17	24.46			

Table D.4 Least significance difference on Δa* of uncoated and coated CLT exposed to 360 hours of artificial weathering

Alpha		0.05
Error Degrees of Freedom		12
Error Mean Square		0.74
Critical Value of t		2.18
Least Significant Difference		1.53
t Grouping[1]	**Mean**	**Coat**
A	2.03	Control
B	0.27	I
B		
B	0	C
B		
B	-0.20	F
B		
B	-0.40	J
B		
B	-0.93	A

[1]Means with the same letter are not significantly different.

Table D.5 Changes in Δb* of uncoated and coated CLT exposed to 360 hours of artificial weathering

Source	DF	Sum of Squares	Mean Square	F Value	p<0.05
Coat	5	218.30	43.66	20.69	<.0001
Error	12	25.32	2.11		
Corrected Total	17	243.62			

Table D.6 Least significance difference on Δb* of uncoated and coated CLT exposed to 360 hours of artificial weathering

Alpha			0.05
Error Degrees of Freedom			12
Error Mean Square			2.11
Critical Value of t			2.18
Least Significant Difference			2.58
t Grouping[1]		**Mean**	**Coat**
	A	7.33	Control
	B	0.17	A
	B		
	B	-0.27	F
	B		
C	B	-1.13	C
C	B		
C	B	-2.37	J
C			
C		-3.47	I

[1]Means with the same letter are not significantly different.

Table D.7 Color changes (ΔE*) of uncoated and coated CLT exposed to 360 hours of artificial weathering

Source	DF	Sum of Squares	Mean Square	F Value	p<0.05
Coat	5	270.42	54.08	18.07	<.0001
Error	12	35.91	2.99		
Corrected Total	17	306.32			

Table D.8 Least significance difference on ΔE* of uncoated and coated CLT exposed to 360 hours of artificial weathering

Alpha			0.05
Error Degrees of Freedom			12
Error Mean Square			2.99
Critical Value of t			2.18
Least Significant Difference			3.08
t Grouping[1]		**Mean**	**Coat**
	A	12.97	Control
	B	5.53	J
	B		
C	B	4.20	I
C	B		
C	B	2.87	A
C			
C		1.80	C
C			
C		1.67	F

[1]Means with the same letter are not significantly different.

Table D.9 Changes in lightness(ΔL*) of uncoated and coated CLT exposed to 1800 hours of artificial weathering

Source	DF	Sum of Squares	Mean Square	F Value	p<0.05
Coat	5	264.62	52.92	36	<.0001
Error	12	17.64	1.47		
Corrected Total	17	282.26			

Table D.10 Least significance difference on lightness of uncoated and coated CLT exposed to 1800 hours of artificial weathering

Alpha		0.05
Error Degrees of Freedom		12
Error Mean Square		1.47
Critical Value of t		2.18
Least Significant Difference		2.16
t Grouping[1]	**Mean**	**coat**
A	-1.67	F
B	-7.60	C
C	-11.03	I
C		
C	-11.27	Control
C		
C	-12.00	J
C		
C	-12.90	A

[1]Means with the same letter are not significantly different.

Table D.11 Changes in Δa* of uncoated and coated CLT exposed to 1800 hours of artificial weathering

Source	DF	Sum of Squares	Mean Square	F Value	p<0.05
Model	5	59.32	11.86	10.31	0.0005
Error	12	13.81	1.15		
Corrected Total	17	73.13			

Table D.12 Least significance difference on Δa* of uncoated and coated CLT exposed to 1800 hours of artificial weathering

Alpha			0.05
Error Degrees of Freedom			12
Error Mean Square			1.15
Critical Value of t			2.18
Least Significant Difference			1.91
t Grouping[1]		**Mean**	**Coat**
	A	3.23	A
	A		
	A	3.00	C
	B	0.73	J
	B		
C	B	-0.63	I
C	B		
C	B	-0.77	Control
C			
C		-1.33	F

[1]Means with the same letter are not significantly different.

Table D.13 Changes in Δb* of uncoated and coated CLT exposed to 1800 hours of artificial weathering

Source	DF	Sum of Squares	Mean Square	F Value	p<0.05
Coat	5	264.10	52.82	13.48	0.0001
Error	12	47.03	3.92		
Corrected Total	17	311.13			

Table D.14 Least significance difference on Δb* of uncoated and coated CLT exposed to 1800 hours of artificial weathering

Alpha			0.05
Error Degrees of Freedom			12
Error Mean Square			3.92
Critical Value of t			2.18
Least Significant Difference			3.52
t Grouping[1]		**Mean**	**Coat**
	A	-1.30	A
	A		
	A	-1.63	F
	A		
B	A	-3.43	C
B			
B		-5.47	Control
B			
B		-6.67	J
	C	-12.60	I

[1]Means with the same letter are not significantly different.

Table D.15 Color changes (ΔE*) of uncoated and coated CLT exposed to 1800 hours of artificial weathering

Source	DF	Sum of Squares	Mean Square	F Value	p<0.05
Coat	5	361.76	72.35	19	<.0001
Error	12	45.69	3.81		
Corrected Total	17	407.45			

Table D.16 Least significance difference on ΔE* of uncoated and coated CLT exposed to 1800 hours of artificial weathering

Alpha			0.05
Error Degrees of Freedom			12
Error Mean Square			3.81
Critical Value of t			2.18
Least Significant Difference			3.47
t Grouping[1]		**Mean**	**Coat**
	A	16.87	I
	A		
B	A	13.90	J
B			
B		13.37	A
B			
B		12.63	Control
	C	8.90	C
	D	2.87	F

[1]Means with the same letter are not significantly different.

APPENDIX E

ANALYSIS OF VARIANCE AND T-TEST FOR WEIGHT LOSS CAUSED BY *G. trabeum*

Table E.1 Weight loss of CLT samples exposed to brown rot fungi

Source	DF	Sum of Squares	Mean Square	F Value	p<0.005
Model (Coat)	5	3604.14	720.83	23.15	<.0001
Error	24	747.15	31.13		
Corrected Total	29	4351.29			

Table E.2 Least significance difference of CLT samples exposed to brown fungi.

Alpha		0.05
Error Degrees of Freedom		24
Error Mean Square		31.13
Critical Value of t		2.06
LSD		7.28
t Grouping[1]	**Mean**	**Coat**
A	29.15	J
A		
A	28.73	Control
A		
A	26.17	F
B	10.07	I
B		
B	9.30	A
C	1.33	C

[1]Means with the same letter are not significantly different.