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Innovation with Cellulose Nanomaterials

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Cellulose nanocrystals (CNCs) are extracted from lignocellulosic biomass via hydrolytic processing, typically using strong sulfuric acid. CNCs are negatively charged, nano-scaled particles that possess unique properties, most notably is their ability to self-assemble to produce structural colour. Structural colour differs from typical pigmented colour—resulting from the transfer of electrons between atoms—in that it is permanent unless the material is damaged. CNCs share this phenomenon with other natural materials like butterflies and beetle skin, to name a couple. In water, CNCs spontaneously form “chiral nematic” liquid crystals, where these crystals organise into a helical structure. Owing to their electromagnetic properties, CNCs self-assemble under the influence of the earth’s magnet into pseudo-planes, where the CNCs make a specific angle with respect to the director, or vertical vector passing through these pseudo-planes. The angle shifts at each pseudo-plane, and the distance it shifts over 360^o is referred to as the pitch. The pitch can primarily be manipulated by changing the pH or ionic strength, and upon water evaporation, a film of CNCs could retain the chiral nematic structure. This is a unique capability that allows the production of structural colour from a sustainable resource for industrial applications. CNCs can thus be used in paints and coatings applications, as well as a template to create mesoporous, chiral inorganic and organic structures for photonic and optoelectronic applications.

CNCs are also characterised by their ability to manipulate and control the rheological response of polymers, suspensions and composites. Having a high degree of crystallinity (> 90%), approaching that of a pure cellulose molecule, CNCs have high tensile strength (ca. 10 GPa) and Young’s modulus (ca. 140 GPa) thus rendering them stronger and stiffer than high-tenacity synthetic fibres like Kevlar 29 and Aramid. This can translate into creating hard coatings and varnishes, and the combination of structural colour and high strength/stiffness opens up a multitude of potential industrial applications.

Different from CNCs, cellulose filaments (CFs) can be produced by mechanically refining wood-pulp fibres. CFs are a heterogeneous network-like structure of fibre fragments and fibrillated material. If a combination of high-shear homogenisation and a suitable chemical of enzymatic treatment are employed to the starting wood-pulp fibres, one can produce cellulose nanofibrils (CNFs) that have nanometric cross-sectional dimensions and micron or submicron lengths. CNFs are also netowork-like, but much finer in dimension than CFs, however much larger than CNCs. CNFs would be highly suitable to producing homogeneous films, or they can be used as rheology modifiers in polymer systems in food, paints and coatings, for example.

This new generation of cellulosic nanomaterials and nanostructures will play a significant role in the development of sustainable, eco-efficient, bio-based materials and structures for industrial, medical and consumer applications.

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Studies of Lignin as Wood Preservative – A Literature Review

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Lignin is the most abundant aromatic biomaterial on earth and is abundantly available as a by-product from the pulp and paper industry. Lignin has attracted a lot of global research interest for applications such as adhesives, foam and carbon fibre.

A brief literature search has been conducted in order to review the potential of lignin as a wood preservative and the investigative work done in this application area to date by different researchers.

Chirkova et al. (2009) investigated the efficacy of pine treated with aqueous alkali lignin solutions. The lignin filled partially (by 13%) the lumens and intercellular spaces of the wood. This was hypothesized to hamper the diffusion of fungal enzymes, though other mechanisms may have also contributed to this effect. Despite the high hydrophilicity of the wood, the lignin treatment was associated with enhanced decay resistance.

Chirkova et al. (2011) investigated the bio-protection properties of different lignin types by treating pinewood with vacuum impregnation of aqueous lignin solutions of low concentrations (0.5-1.0%) and then exposing the treated samples to three brown rot fungi (*Coniophora puteana*, *Postia placenta* and *Gleophyllum trabeum*) and one white rot fungus (*Coriolus versicolor*) following the standard procedure EN 113. The results showed that the impregnation of wood with lignin-water colloids or solutions of low concentrations of lignin enhanced the decay resistance against brown and white-rot fungi. Kraft lignin, hydrolysis lignin, alkali lignin and industrial lignosulfonates showed the highest efficacies, giving low or negligible mass losses.

Dos Santos et al. (2012) reported that pine sapwood samples treated with a solution of Eucalyptus organosolv lignin at 1% in water/ketone showed higher decay resistance to both white-rot and brown-rot fungi than the untreated samples. However, weight losses in control samples were very low indicating that the conditions of the test were not conducive to fungal growth.

Durmaz et al. (2015) reported that kraft black liquor could inhibit fungal activity and improve wood biological durability against brown-rot fungi. In their study, sapwood samples of Scots pine were treated with black liquor from a kraft pulping process of both sapwood and heartwood of Scots pine (*Pinus sylvestris* L.) at different concentrations (2.5, 5.0, and 7.5%). The untreated and treated wood samples were then exposed to two different brown-rot fungi, *C. puteana* and *P. placenta*, according to EN 113 standards. After six weeks of exposure to both fungi, the weight loss of treated samples was found to be less than 3%, in comparison with 25-30% weight loss from the untreated control samples. However, the authors made no mention of neutralizing the pH of the black liquor, and no alkaline controls were included, so it's possible the inhibitory effects were simply due to the high pH of the treatment.

In addition, lignin has been demonstrated to be a suitable material for fixation of metals in wood. Lin (1993) describes a method by which wood was impregnated with a wood preservative composition consisting an aqueous solution of ammonium salt of lignin and ammonia complexes of certain metal cations such as $Cu(NH3)_4^{2+}$, $Zn(NH_3)_4^{2+}$, and $Hg(NH_3)_2^{2+}$. This patent claims that sufficient penetration and retention of the wood preservatives can be achieved. Furthermore, the lignin can be selected from the group consisting of alkali lignin, organosolv lignin, partially desulfonated sulfite lignin, and modified alkali or organosolv lignin, which means that both major technical lignins (kraft and sulfite) currently available from lignin manufacturers are adaptable to the patented method. The patent does not provide any efficacy data on these preservatives.

In summary, the research work in the area of lignin application as a wood preservative appears to be still quite limited, but has shown that the use of lignin may enhance wood's natural decay resistance. The performance of lignin as a wood preservative depends in large part on how it is sourced and applied to wood. All currently available results were based on laboratory tests of small samples of treated wood. Field testing would be required to provide a comprehensive understanding of the utility of lignin as a wood protection agent.

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DEGRADATION OF WOOD BENEATH THE COATINGS: A WAY OF MONITORING THE COATING STATE

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Summary

Nowadays, it is not common knowledge to know when it is appropriate to re-apply a new coating. The aim of this study was to find an indicator to monitor the coating state. Different wood opaque paints have undergone weathering in both Florida and Arizona. The results confirm the necessity to have a tailor made solution for monitoring the coating state. The characterization of the wood beneath the coating has been done with an ATR-FTIR. The monitoring of both the lignin and the cellulose crystallinity has been realised. It appeared that the lignin seems to indicate an early loss of performance of the coating protective layer. However some limits exist in the experimental design and further experiment should be processing.

1. Introduction

Among strategies used to protect wood against weathering, the use of paint as coatings is the most widespread (Weiss 1997,Shukla, et al. 2009,Singh, et al. 2001). They are economic, easy to apply, and allow having any aesthetic aspect wished by customers. A paint is composed of a resin, a solvent or a diluent, several additives, and some pigments and/or dyes (Bulian and Graystone 2009). The formulation of the paint has impact on its resistance (Pintus, et al. 2016,Pintus and Schreiner 2010). In fact, even if the coating protects the wood, it undergoes degradation from the weathering (Shukla, et al. 2009,Schmid 1988,Estrada 1967,Chiantore and Lazzari 2001,Rosu, et al. 2009). For both the wood and the coating, photo-degradation is the fastest and the strongest degradation (Feist and Hon 1984,Hon and Chang 1984,Feist 1989). Unlike concrete, steel, or aluminium, the wood reacts quickly to the weathering (Feist 1983). Wood compounds, especially lignin, are able to absorb light from short wavelengths (from 295 to 400nm) (Pandey 2005,Kalnins 1984). On the other hand, cellulose can be modified by visible light (from 400 to 800nm)(Derbyshire and Miller 1981).

Eventually, it is necessary to re-apply a new layer of paint to avoid the loss of the protective effect. The right moment to do depends on many characteristics such as the formulation of the paint, the region of utilization, the wood used, and the intensity of weathering (Williams, et al. 2000,Grüll, et al. 2014,Jacques 2000,Browne 1962). However, most often a generic time line is given by the manufacturer through their guarantees. Due to the lack of accuracy, the re-application is rarely at the right time as it can be done either too early or too late. If it is done early or in the right moment, the work to do is merely to apply a new layer. However, if it is done too late, the work to do is more complicated (Evans, et al. 2015). The wood polymers beneath the coating undergo degradations and modifications. It can lead to a phenomenon called "wood surface inactivation" (Aydin and Colakoglu 2005,Nussbaum 1999). It describes a non-reversible reaction of the wood surface. The durability of the layer is significantly decreased, and sanding the surface becomes necessary before re-application of paint (Williams and Feist 2001,Jirouš-Rajković, et al. 2007). Therefore, it is necessary to discover a tailor-made solution for monitoring when the coating start to fail.

In this study, the state of two wood polymers: lignin and cellulose, and their sensitivity to light were investigated. The hypothesis is to answer whether or not these polymers can be used as indicator of the premature loss of coating performance.

For this purpose, four acrylic paints are undergone accelerated weathering in Florida (Q-lab, USA) and Arizona with sun light concentrator (Q-lab, USA). Due to the higher factor of acceleration in Arizona, for the same time of exposure, more energy is received by the samples. A first overview of the samples after degradation allowed noticing four different resistances. It confirmed the need to have a tailor-made monitoring system. The wood used in this study is white spruce (*Picea glauca* (Moench Voss)). The samples have been characterized by ATR-FTIR after removing the paints with acetone. The results shown are promising and monitoring of the lignin seems to be a suitable solution.

2. Methodology

- **Paints**

Four acrylic paints were obtained from the industry for the experiment. They are opaque paints with 4 different colours: paint 1 (white), paint 2 (beige), paint 3 (red) and paint 4 (blue). They are constituted of two kinds of acrylic base either 1501 (paint 1 & 2) or 1506 (paint 3 & 4), and several dyes and pigments. The difference between the two kinds of acrylic base is mainly the addition of titanium dioxide in the 1501. Paint 1 (white) is a 1506 base with a strong concentration of titanium dioxide for the ability to be used without other additives.

- **Accelerated exposures**

Arizona

Samples were exposed in a "Q-trac sunlight concentrator testing" provided by Q-lab (USA) for six months. Cycle 1 of ASTM G90-10 standard test method "Standard Practice for Performing Accelerated Outdoor Weathering of Non-metallic Materials Using Concentrated Natural Sunlight" was used. This technology is equipped with 10 mirrors, which allow concentrating and reflecting the total spectrum of the sun. The contribution of the water is taken into account with a water spray three times a day.

Florida

Samples were exposed in direct exposure at 45° in the devices provided by Q-lab (USA) for twelve months. The ASTM G7-13 standard test method "Standard Practice for Atmospheric Environmental Exposure Testing of Non-metallic Materials" was used.

Of the four samples used in the experiment, two were exposed in Arizona, and the other two were exposed in Florida. The data provided by Q-lab is recapitulated in table 1.

Table 1: Length of exposure for each treatment. Quantities of MJ/ m² received by the samples provided by Q-lab.

Exposure	Florida		Arizona	
Time	6 months	12 months	2 months	6 months
MJ Total/ m²	3180	6300	9091	27273

- **ATR-FTIR Spectroscopy Analysis**

FTIR spectroscopy experiments were carried out using a Spectrum 400 from Perkin Elmer (UK) equipped with an attenuated total reflection accessory (ATR). With the aim to analyze the wood under the paint, acetone was used to remove the paint. The resolution was set at 4 cm^{-1}, 64 scans were recorded for each analysis, and the scanning range was from 650 cm^{-1} to 4000 cm^{-1}.

Ten analyses were performed at height different locations on each sample. The data from these spectra were extracted with GRAMS software form Thermo Scientific (USA).

- **Statistical Experiments**

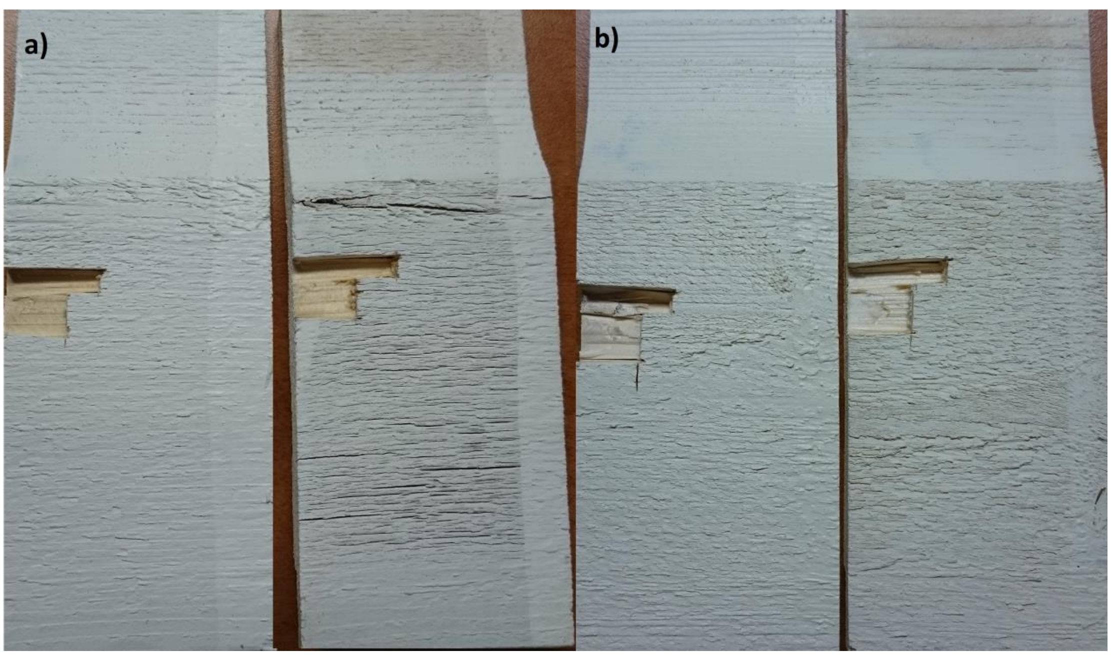
Only one sample by treatment was sent to Florida and Arizona. The size of the samples was enough for performing ten analyses. Thus, statistical studies could be done. All these tests have been realized with RStudio software. A plot on the variables allowed for the validation of the distribution. The difference into a variable was checked with ANOVA. The significant differences were conducted with Tuckey HSD (honest Significant Difference) on each treatment.

3. Results and discussion

- **Macroscopically**

Figure 1 shows the non-degraded sample (left) and the most degraded sample (right) for each paint. The intermediate samples are not shown to maintain readability. Some differences can be observed between both samples. For paints 1 and 4, the wood beneath the coating appears in some spots. For the others, the coating seems to have remained bonded to the wood surface.

The samples were painted and exposed at the same time and in the same condition. For all these paints, the manufacturer guaranteed the same lifespan before the application of a new coat. In regards to the observations, the resistance to weathering seems different. These results confirm the need to have an indicator for monitoring the early fails of the coating. In this case, guarantees made by manufacturers on the effectiveness of the paint are not tailor made to the customer's environment and could result in unwanted state of material. The wood could have undergone degradation causing its surface inactivation. An infrared analysis will enable us to answer if these degradations could be monitored.



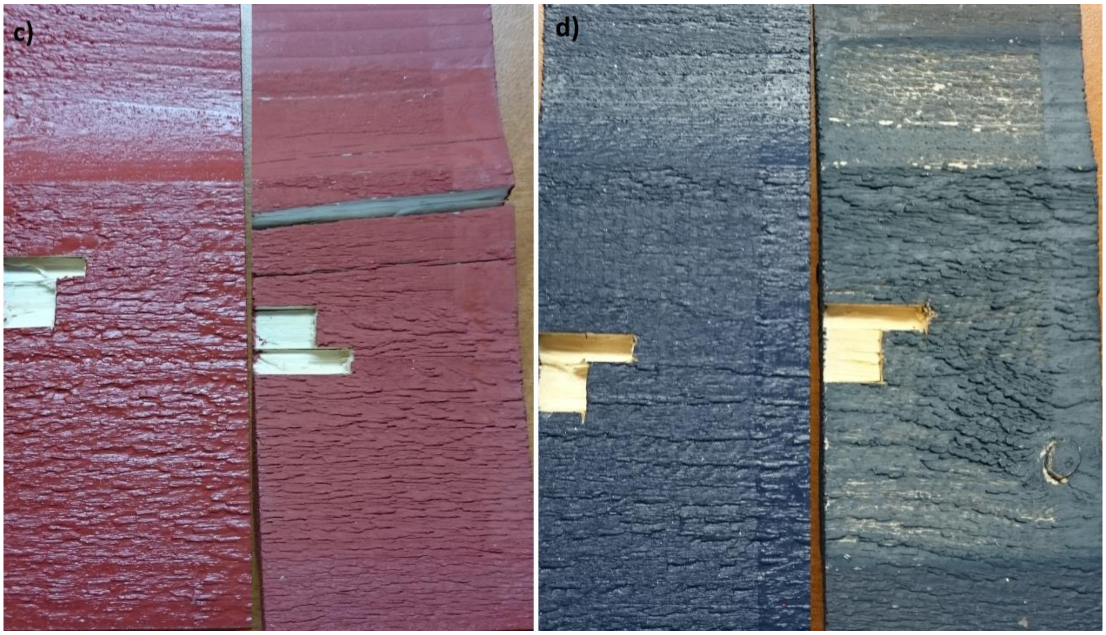


Figure 1: Pictures of samples from the experiment, the left samples correspond to the controls and the right samples correspond to the most degraded samples. a) paint 1, b) paint 2, c) paint 3 and d) paint 4.

- **Infrared Analysis**

On the infrared spectra (not shown), two strong contributions can be noticed; the –OH stretching at 3300-4000cm^{-1}, and the C-H stretching at 2800-3000cm^{-1}. Both are basic patterns found on wood FTIR spectra. With the aim to answer at the hypotheses and to find an early monitoring for the coating degradation, two parameters were studied: the rate of lignification, and the crystallinity index of the cellulose.

The rate of lignification has been followed by the study of the ratio I_{1510} / I_{1375} on infrared spectra. The peak at 1510cm^{-1} corresponds to a pure contribution from the lignin, and the peak at 1375cm^{-1} corresponds to a carbohydrate contribution not affected by photo-degradation (Pandey 2005,Pandey and Pitman 2003,Ganne-Chédeville, et al. 2012). The more the ratio is decreased, the more the lignin is affected by the photo-degradation. Figure 2 shows the rates of lignification of the wood beneath each paint. The results for both Arizona and Florida are presented on the same figure. Thus, correlations are easier to notice. ANOVA tests were performed on each paint and showcase significant decreases of the rate of lignification in function of the MJ/ m² received by the samples. The table 2 shows the different variations of the rate of lignification. The groups A, B, C and D correspond to groups with significant differences with α=0.05.

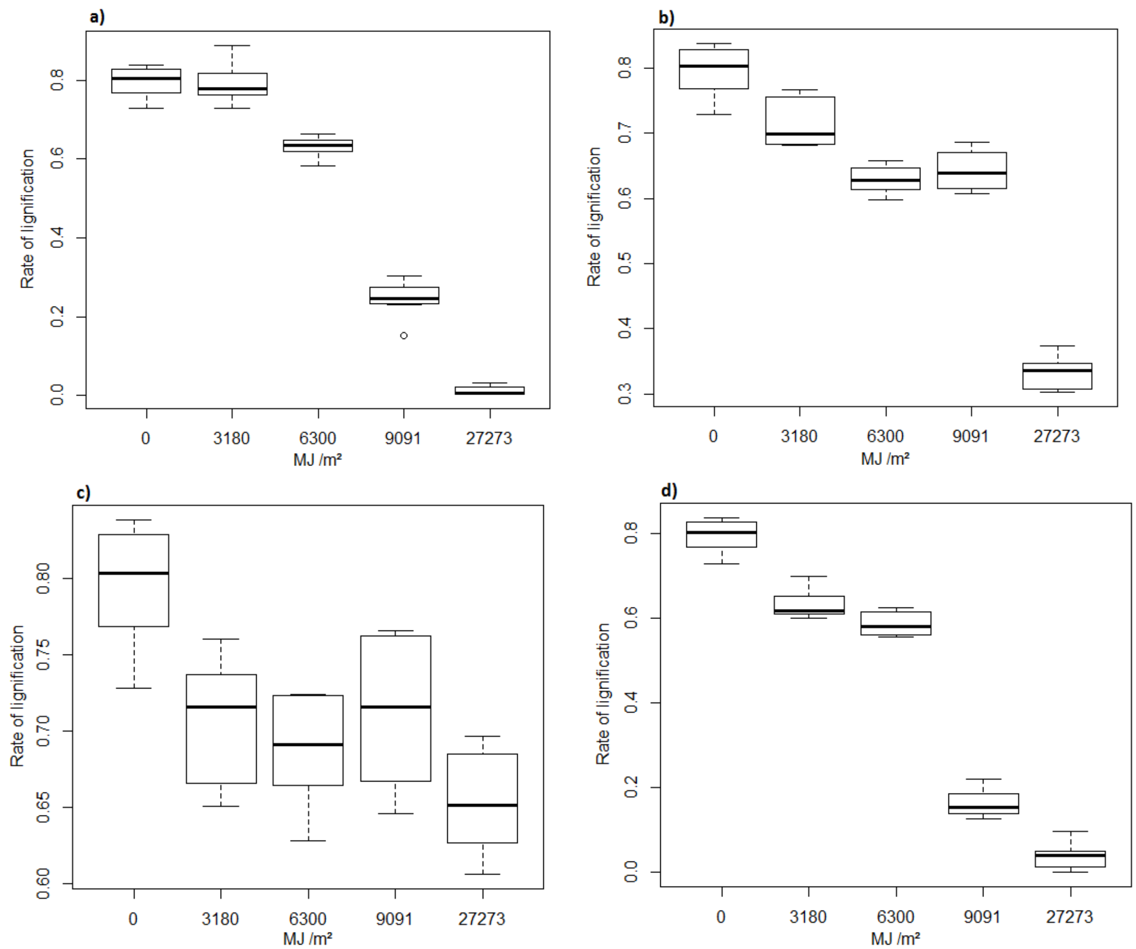


Figure 2: Variation of the rate of lignification in function of the MJ/ m² received by the samples.

It appears that none of these paints allows us to have a total protection of the wood. Four different level of protection can be observed. Even for the paints with the same base, the results are extremely different. Thus, the two 1506 bases, paint 3 and paint 4, are provided the best and the worst wood protection respectively. For paint 3, the difference between the control and the most exposed is 18%, while it is 95% for the paint 4. This extreme degradation can be explained by the loss of protective layer for paint 4 as it is the most degraded sample. This result emphasizes the importance of paint composition on the coating durability, and on the wood protection.

Table 2: Average values of the rate of lignification as function of the MJ/ m² received by the samples. The different letters A, B, C and D indicate statistical differences (Tukey test = 0.05).

MJ /m²	Paint 1 (1501)	HSD	Paint 2 (1501)	HSD	Paint 3 (1506)	HSD	Paint 4 (1506)	HSD
0	0.7958	A	0.7958	A	0.7958	A	0.7958	A
3180	0.7921	A	0.7158	B	0.7058	B, C	0.6330	B
6300	0.6313	B	0.6290	C	0.6887	B, C	0.5876	B
9091	0.2454	C	0.6430	C	0.7126	B, C	0.1621	C
27273	0.0125	D	0.3321	D	0.6535	C	0.0371	D

A similar result is observable for paint 1. A loss of the protective layer has occurred on the most degraded sample. It results in a lesser rate of lignification than observed on the most degraded sample, the paint 4.

Paint 1 and paint 4 correspond to the most degraded samples. An ANOVA between these two results 0.0125 (paint 1) and 0.0371 (paint 4) gives a P=0.0552 with $\alpha=0.05$. There is no significant difference on the rate of lignification when they are not being protected by the coating. The loss of the protective layer leads to the same strong lignin degradation.

It is interesting to notice that even when a protective layer remains, the lignin degradation occurs. It is observable for all the paint, and especially for paint 2. The most degraded sample of this paint has a decrease of its rate of lignification by 58%, even if the coating is still present. The lignin is sensitive at short wave lengths like UV. Its degradation demonstrates the UV permeability of the coating.

Figure 3 shows the crystallinity index calculated by the ratio I_{1316}/I_{1335}. Both of these contributions correspond to the cellulose. This one can be found with two forms: amorphous cellulose and crystalline cellulose. The peaks at 1316cm^{-1} and 1335cm^{-1} correspond to amorphous and crystalline cellulose respectively (Nelson and O'Connor 1964,Colom and Carrillo 2002). An increase of this ratio corresponds to an increase of the cellulose crystallinity.

The ANOVA were performed for each paint. No significant difference has been found between the non-degraded, and the most degraded sample paint 3. For paint 1, 2 and 4, significant differences have been found between the non-degraded, and the most degraded samples. The table 3 summarizes the significant differences for each paint.

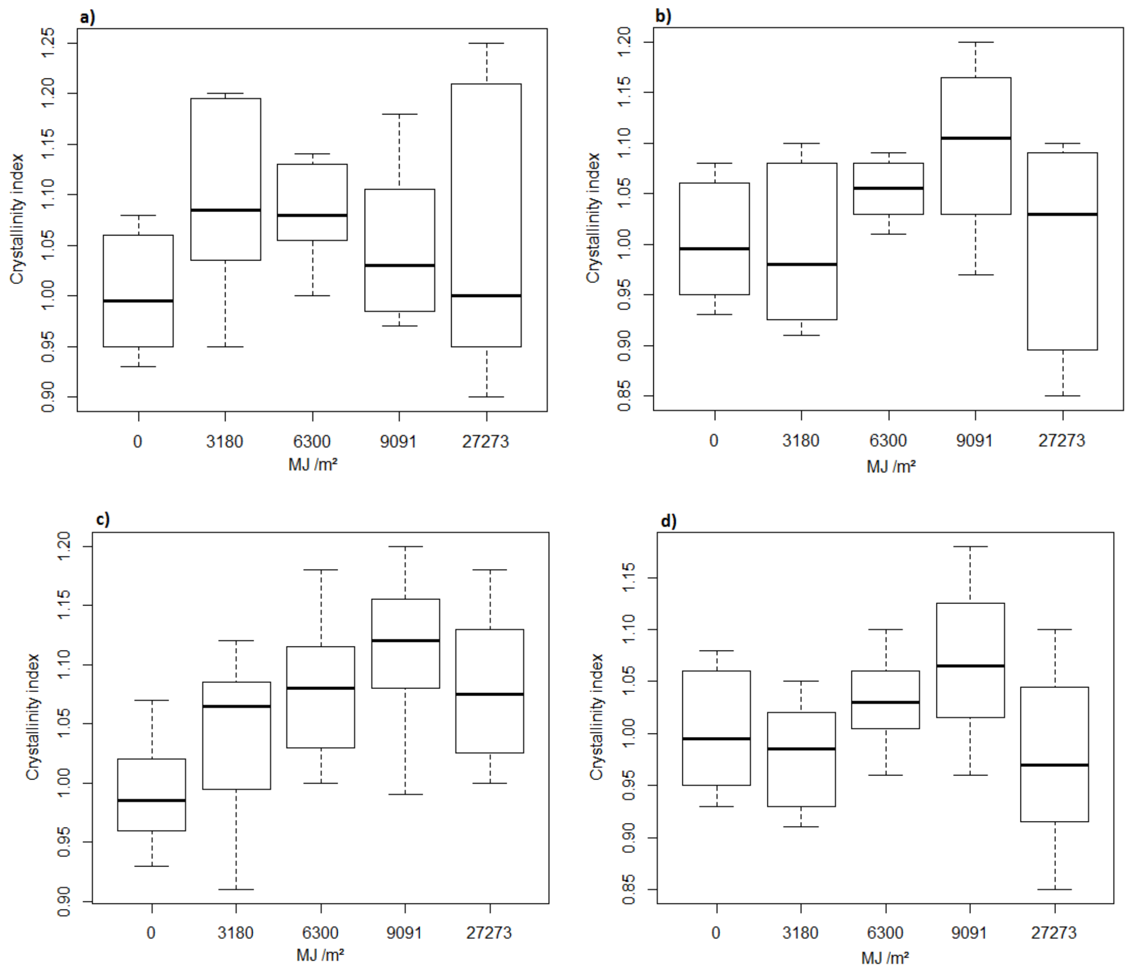


Figure 3: Variation of the cellulose crystallinity in function of the MJ/ m² received by the samples.

Unlike lignin, the cellulose is sensitive to the visible light. Due to the presence of dyes and pigments, the paints appear colored. This is due to the transmission and the emission properties of the light on the paint. In short, if the paints appear colored, it means that the visible lights cannot go through the paint layer. The wavelengths are scattered and some of them will reflect to the eyes, being interpreted by the brain as colors. As soon as the protective layer fails, visible light can go through the paint layer and the cellulose undergoes modification. It means that these significant differences on the cellulose crystallinity could be the consequence of the loss of the protective layer.

Table 3: Average values of the cellulose crystallinity as function of the MJ/ m² received by the samples. The different letters A, B and C indicate statistical differences (Tukey test = 0.05).

MJ /m²	Paint 1 (1501)	HSD	Paint 2 (1501)	HSD	Paint 3 (1506)	HSD	Paint 4 (1506)	HSD
0	1.0025	A	1.0025	A	1.0025	A	1.0025	A
3180	0.9988	A	0.9976	A	1.0351	A	0.9825	A
6300	1.0262	A	1.0401	A	1.0426	A	1.0313	A, B
9091	1.0921	A, B	1.0438	A,B	1.0824	A	1.0850	B, C
27273	1.1187	B	1.1065	B	1.0663	A	1.1088	C

The goal of this study is to find a good lead to monitor the early degradation of the protective effect. The crystallinity index does not allow us to achieve that goal. In fact, the coating has already failed and wood surface inactivation could occur. Re applying a coating on it could lead to weak bonds between the paint and the wood.

The rate of lignification undergoes modifications even if the coating remains protective. In fact, for paint 3, a lignin modification is observed without cellulose modification.

Assuming the cellulose modification is due to the visible light, implies that the light can go through the paint and that the coating is ineffective. Therefore, if we notice cellulose modification in a sample, it can be concluded that the paint coating is ineffective. The sample just before the first sample to experience cellulose modification shows the breakeven point of the protective effects of the paint coating. The calculation of the decrease of the rate of lignification between this one and the control allows having a value. This value corresponds to a level of lignin degradation where the coating is still efficient. These values are calculated for each paint (Table 4).

Table 4: Maximum decrease of the rate of lignification before the breakeven point of the protective effects of the paint coating.

	Paint 1	Paint 2	Paint 3	Paint 4
Decrease of the rate of lignification	20.7%	21.0%	17.8%	20.5%

The results obtained tend to be around the same value. Consequently, the monitoring of the rate of delignification is quantitative. A decrease of 1/5 of the rate of lignification seems to be a reliable point of no return for this experiment.

However, despite these promising results, some limits to this study must be emphasized. Even if the sample size was enough to do several analyses, the results obtained only give the variability of the sample itself. Therefore, to reach conclusive and statistically significant result, it should be needed to do more experiments. Moreover, the study invests only in spruce and no other species.

4. Conclusions

The macroscopic results show the necessity to monitor the coating degradation. The composition and the formulation of the paint is an important factor in the coating durability. The generic guarantees from the manufacturers do not take into account the variability given by them. Thus, it is rare to have a reapplication of a new layer at the right moment. If this one is done too late, damages can lead to a surface inactivation and lead to a low durability of the new layer.

The study of both polymers, lignin and cellulose, has enabled to have a first lead. Due to the sensitivity of the cellulose to the visible light, its monitoring could be too late to identify wood surface inactivation at the right time. In the case of opaque coatings, the visible light cannot go through the paint layer. The cellulose modification is a consequence of the failure of the coating's protective effect. On the other hand, the lignin is sensitive to the UV part of the light. Due to some defects as well as permeability in the protective layer against UV, lignin can undergo degradation even if the coating is still present. The quantification of the rates of lignification for each treatment has showed a relation between the values obtained, and the coating state. Thus, the rate of lignification seems to be a reliable early monitoring system. In this experiment, a value indicating a point of no return could be estimated. However, due to a lack of true replication, no conclusion can be generalised yet. Additional work is needed to confirm this monitoring and to provide more accurate data.

5. Acknowledgements

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FIVE-YEAR FIELD TEST OF PRESERVED CANADIAN SPECIES IN KOREA AND CANADA

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Abstract

The objective of this work was to assess the field performance in Korea of Canadian softwood species preservative-treated to Canadian standards. Western hemlock and white spruce were incised and pressure-treated with alkaline copper quaternary (ACQ) or copper azole (CA), based on the Canadian CSA O80 Series-08 standards. A ground contact stake test and an above-ground covered test were installed in Jinju, Korea. End-matched material for ground contact exposure only was also installed in at a field test site in Canada. After five years of exposure, no decay was found in preservative-treated samples at either test site, while in untreated material decay, and particularly termite attack in Korea, were well advanced.

Introduction

Korea is an important export destination for Canadian softwood lumber. Before 2013, much of this lumber was treated with preservatives, without incising, by local treaters for landscaping projects. The use of SPF for preservative treatment was anticipated to drop when the Korean government announced new regulations on inspection and quality assurance for treated wood. This is because it is impossible to meet the 10 mm penetration requirements of Korean standards with this species group without incising. In 2010 FPInnovations was asked to conduct field tests of preservative-treated Canadian softwood species in Korea to demonstrate the performance of treated Canadian softwood, in collaboration with Gyeongnam National University for Science and Technology (previously operated as Jinju National University). The treatment was to meet the retention and penetration requirements of Canadian Standards Association UC3.2, Residential Product Group C for above-ground or UC4.1 Residential Product Group D for ground contact applications (CSA 2008).

Penetration requirements in Canadian standards have been reduced compared to Korean standards based on long-term performance data (Morris and Ingram 2011; Morris *et al.* 2012) and fundamental work on how shell treatments work (Choi *et al*. 2001; 2002; 2004; Morris *et al*. 2004). The major objective of this study was to confirm that Canadian wood treated to lower penetration requirements will perform well in the Korean climate. Early results were published after two years exposure in Korea and two years in Canada (Wang *et al.* 2014). This paper presents inspection results after five years in test at both sites.

Materials and Methods

Sample Preparation and Treatment

The test methods were essentially as per AWPA E7-09 for the ground contact stake test and AWPA E18-06 for the ground proximity test (with a slight deviation in sample size. 38 mm thick samples were used in the study, instead of 20 mm thick samples recommended in the standard). Western hemlock **(***Tsuga heterophylla* Raf. Sarg.**) a**nd white spruce (*Picea glauca* Moench. Voss), both nominal 2×4 dimension lumber (38 × 89 mm), were sorted from western hem-fir and western SPF, respectively. White spruce represents some of the more refractory Canadian softwood species used for preservative treatment while western hemlock is somewhat more treatable, especially when incised (Cooper and Morris 2007). Alkaline copper quaternary (ACQ-D), was supplied by Timber Specialties, and copper azole (CA-B), was supplied by Arch Chemicals. All lumber was incised prior to treatment.

Optimal treating solution strengths for each target retention were established by a trial treatment of each species using ACQ at low solution strength. The incised double-length stakes and above-ground samples were then treated separately for each species and test. The treating schedule used for both species was an initial 30 minute vacuum at a minimum 22” Hg (75 kPa), followed by 2 hours at a pressure of 150 psi (1034 kPa), then a final 15 minutes of vacuum at a minimum 22” Hg (75 kPa). All treatments were carried out at 20 ± 2°C. After the treatment a weight uptake (gauge retention) was calculated for each sample. All of the treated lumber was stickered and allowed to air dry under cover in the FPInnovations compound. Retention analysis was used to select 13 double length lumber pieces from each target retention/species group for the ground-contact, or the above-ground field efficacy tests. The treated lumber pieces were then cut into two daughter field test samples and the fresh cut end was treated with a field cut preservative containing copper naphthenate (2% Cu). One set of 460mm long stakes and the 125mm long above-ground samples were installed in Korea in November 2010. The other set of the ground-contact material was installed in Canada in September 2011 for comparison between the two test sites.

Sample Analysis

Analysis biscuits, each approximately 50 mm long, were cross-cut from the centre of each treated double length lumber piece for chemical analysis. The penetration was detected by applying chrome azurol S to the surface of samples to show copper penetration and measured to the nearest millimetre. Samples were taken from a 13 mm assay zone, ground to sawdust, and analyzed for copper retention using x-ray spectroscopy.

Installation

At the field test in Jinju, Korea, 26 ACQ- and 26 CA-treated stakes, plus 10 untreated control samples for each species, were installed, to half their length, with the uncut end of each sample in the soil, in November 2010. The same number of samples was also installed in an above-ground test based on the AWPA E18-06 ground proximity test. The above-ground samples were placed on concrete blocks surrounded by untreated Douglas-fir lumber frames. The shade cloth used for covering the test samples had a solar shading coefficient of 75%. The other set of ground contact stakes (10 per variable) was retained for later installation at FPInnovations' field test site in Petawawa, Ontario, which took place in September 2011.

Test Sites

Gyongnam National University's Korean test site is located on the outskirts of Jinju, a southern city in Korea. The site is on a small hill and surrounded by bamboo and other shrubs. It was newly cultivated after clearance of shrubs before the installation of the test samples in 2010. The site used to be an orchard and the fruit trees were cut down about 15 years ago leaving roots in the ground. The soil appeared to be between clay and sandy soil. The site appeared to have good natural drainage due to the slope of the hill. Jinju has a mixed climate with hot summers and cold winters. Its Scheffer climate index is about 58 (Kim *et al*. 2011), and therefore is within the moderate decay hazard zone (Scheffer 1971; Setliff 1986). This index number is higher than that of the Petawawa test site but close to the index of Prince Rupert, BC (Morris and Wang 2008).

This test site also turned out to have a substantial foraging population of termites. There is little information available on the termite hazards in Korea although there have been anecdotal observations about attacks in temples built with wood. It has been generally described in wood protection textbooks that termites (*Reticulitermes speratus*) exist in areas up to 38° latitude (email communications with Prof. Yoon Soo Kim, Chonnam National University, November 2007). This would include areas south of Seoul including Jinju.

FPInnovations' Canadian test site is located on the grounds of the Petawawa Research Forest near Chalk River, Ontario. The test site is located in a cleared natural forest area surrounded by a mixed coniferous/deciduous forest. Mean daily maximum and minimum temperatures are -7°C and -18°C in January, and 25°C and 13°C in July. The site receives mean annual precipitation of 822 mm. It falls within the moderate decay hazard zone for outdoor above-ground exposure using Scheffer's climate index (Scheffer 1971; Setliff 1986), with a climate index of 48 (Morris and Wang 2008). Frequently, tree seedlings become established in the plot and must be manually removed every few years. The soil is classified as a dark brown loam to a depth of 9 cm, changing to a light brown loam that extends to 18 cm, followed by coarse sand below. The soil has a pH of 6.0 at the surface and 5.4 at a depth of 9 cm, with an average moisture-holding capacity of 25%. The site has a grassy ground cover. Results in the early years indicated that the level of soft rot activity at this site was low compared to other test sites; however this may have been due to removal of topsoil when levelling the site. A new layer of topsoil has built up in the last 50 years and there are areas where soil inhabiting, strand-forming, wood-rotting basidiomycetes, including *Leucogyrophana pinastri*, *Tapinella panuoides*, *Hypholoma fasciculare*, *Serpula himantiodes*, and *Oligoporus balsameus* are very active.

Inspection

In September at Petawawa and November, in Jinju, each stake was removed from the soil and loose grass and dirt were brushed off. The stakes, and the above-ground samples, were then examined visually for indications of decay, such as the presence of fungal mycelium or discolouration. If decay was suspected, the area of interest was gently probed with a metal scraper. Each specimen was then assigned a rating for termite attack and decay, based on the AWPA E7 (2008) grading system:

Decay Rating	Condition	Description
10	Sound	No sign or evidence of decay, wood softening, or discoloration caused by microorganism attack.
9.5	Trace-suspect	Some areas of discolouration and/or softening associated with superficial microorganism attack.
9	Slight attack	Decay and wood softening is present. Up to 3% of the cross sectional area affected.
8	Moderate attack	Similar to "9" but more extensive attack with 3-10% of cross sectional area affected.
7	Moderate/severe attack	Sample has between 10-30% of cross sectional area decayed.
6	Severe attack	Sample has between 30-50% of cross sectional area decayed.
4	Very severe attack	Sample has between 50-75% of cross sectional area decayed.
0	Failure	Sample has functionally failed. It can either be broken by hand due to decay, or the evaluation probe can penetrate through the sample.

Termite Attack Rating	Description
10	Sound
9.5	Trace, surface nibbles permitted.
9	Slight attack, up to 3% of cross sectional area affected.
8	Moderate attack, 3-10% of cross sectional area affected.
7	Moderate/severe attack and penetration, 10-30% of cross sectional area affected.
6	Severe attack, 30-50% of cross sectional area affected.
4	Very severe attack, 50-75% of cross sectional area affected.
0	Failure.

Results

Preservative Treatment

CSA retention requirements for preservative treatment specify a minimum retention of 6.4 kg/m³ for ground contact and 4.0 kg/m³ for above ground applications for ACQ treatment, and 3.3 kg/m³ for ground contact and 1.7 kg/m³ for above ground applications for CA treatment (CSA 2008). The penetration requirements can be reasonably simplified as 8 mm for ground contact applications (residential product Group D) and 5 mm for above ground applications (residential product Group C, CSA 2008; Table 1).

CA and ACQ treatments of white spruce failed to meet the ground contact penetration requirement of 60% of samples with 8 mm, while the hemlock treatments did meet this requirement (Table 2). Above ground, the requirement for 80% of samples to have at least 5 mm penetration was met with CA treatment of both white spruce and hemlock, and ACQ treatment of hemlock, but not for the ACQ treatment of white spruce.

Table 1 Compliance with CSA O80 retention and penetration standard requirements

Test	Species	Preservative	Minimal retention requirements of CSA O80-08 (kg/m³)	Mean assay retention (kg/m³)	Percentage of samples with penetration of ≥8 mm	Percentage of samples with penetration of ≥5 mm
Ground contact	Spruce	CA	3.3	2.8 (1.3)	31	46
	Hemlock			2.8 (0.6)	92	92
	Spruce	ACQ	6.4	5.9 (2.5)	23	69
	Hemlock			6.9 (0.6)	100	100
Above ground	Spruce	CA	1.7	1.7 (0.5)	NA	85
	Hemlock			1.8 (0.2)	NA	100
	Spruce	ACQ	4.0	4.2 (1.6)	NA	69
	Hemlock			4.0 (0.9)	NA	100

Standard deviations are shown in parentheses

Field Inspection

Ground contact in Korea

All samples treated with ACQ or CA showed excellent performance after five years in test with a mean rating of 10 for both decay and termite attack (Table 3), although a few samples (one ACQ-treated hemlock and two ACQ-treated spruce) showed a very small amount of mycelial growth at the bottom ends at the fifth annual inspection. Although this was originally planned as simply a decay test, the site in Jinju unexpectedly had a very severe termite hazard. Termites have remained very active and aggressive in the past five years, with attack evident in untreated ground-contact stakes of both species after only one year of exposure (Table 3). At the second annual inspection, the mean termite ratings for untreated spruce and hemlock were 0.0 and 3.7, respectively. Replacement untreated controls were installed and these also showed rapid attack.

By the fifth annual inspection, of the original untreated white spruce and hemlock stakes, only two untreated hemlock stakes remained in test, with an overall mean rating of 1.2. The majority of the untreated control samples also showed varying degrees of decay, mostly in the areas that the termites had attacked. Due to rapid failure of untreated stakes from termite attack at this site, it is difficult to accurately assess decay, although it appears that untreated white spruce was decaying more rapidly than hemlock.

Table 2 Performance of wood in ground contact in Korea

Test	Species	Target ret'n (kg/m^3)	Analysis by FPInnovations		Mean AWPA Rating									
			Mean ret'n (kg/m^3)	Mean pen. (mm)	Year 1		Year 2		Year 3		Year 4		Year 5	
					Decay	Term-ites	Decay	Term-ites	Decay	Term-ites	Decay	Term-ites	Decay	Term-ites
None	Spruce	none	NA	NA	9.8 (0.5)	5.8 (2.9)	5.3 (4.6)	0.0 (0.0)	5.3 (4.6)	0.0 (0.0)	NA	0.0 (0.0)	NA	0.0 (0.0)
	Hemlock	none	NA	NA	10.0 (0.2)	7.0 (1.6)	8.3 (4.1)	3.7 (3.3)	7.3 (3.6)	3.1 (3.4)	7.2 (3.5)	2.7 (3.3)	5.4 (3.3)	1.2 (2.5)
CA	Spruce	3.3	2.8 (1.3)	5.6 (3.5)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)
	Hemlock	3.3	2.8 (0.6)	12.3 (2.5)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)
ACQ	Spruce	6.4	5.9 (2.5)	5.8 (3.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	9.9 (0.2)	10.0 (0.0)
	Hemlock	6.4	6.9 (0.6)	12.8 (0.6)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.1)	10.0 (0.0)

Standard deviations are shown in parentheses

Above ground in Korea

As was the case with the ground-contact stakes, the CA- and ACQ-treated above-ground test samples were not attacked by decay or termites during the five years of exposure in the ground proximity test. In the untreated controls no decay or termite attack was noted after one year (Table 4). By the second and third year, early decay had become established in several untreated samples with average ratings around 9.3 for both species. The deterioration caused by decay continued to progress, particularly in spruce where the mean rating was 6.1 at five years. A new observation at the third annual inspection was that the termites had reached three of ten untreated samples of each species through mud tubes built from the ground, and had damaged those samples, giving average ratings around 9.3. By the five-year inspection, five hemlock and seven spruce samples were attacked by termites, with one hemlock and four spruce samples rated as 0. The concrete blocks appeared to retain moisture for the test samples placed on them creating suitable conditions for both decay and termite attack.

Table 3 Performance of wood above ground in Korea

Test	Species	Target ret'n (kg/m³)	Analysis by FPInnovations		Mean AWPA Rating									
			Mean ret'n (kg/m³)	Mean pen. (mm)	Year 1		Year 2		Year 3		Year 4		Year 5	
					Decay	Term -ites	Decay	Term -ites	Decay	Term -ites	Decay	Term -ites	Decay	Term -ites
None	Spruce	none	NA	NA	10.0 (0.0)	10.0 (0.0)	9.3 (0.6)	10.0 (0.0)	9.3 (0.6)	9.3 (1.2)	9.0 (0.8)	8.4 (2.5)	8.1 (0.7)	7.4 (3.4)
	Hemlock	none	NA	NA	10.0 (0.0)	10.0 (0.0)	9.4 (0.8)	10.0 (0.0)	9.2 (0.7)	9.2 (1.3)	8.7 (0.9)	7.1 (3.1)	6.1 (3.6)	4.6 (4.4)
CA	Spruce	1.7	1.7 (0.5)	8.2 (3.6)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)
	Hemlock	1.7	1.8 (0.2)	12.5 (1.9)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)
ACQ	Spruce	4.0	4.2 (1.6)	5.0 (1.7)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)
	Hemlock	4.0	4.0 (0.9)	12.8 (0.8)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)

Standard deviations are shown in parentheses

Ground contact in Canada

In contrast to the Korea site, early to moderate decay was found in some of the ACQ- and CA-treated stakes at the five-year inspection, particularly in spruce. CA-treated spruce had a mean rating of 9.5 and ACQ-treated spruce had a mean rating of 9.3. CA-treated hemlock was still in excellent condition with a mean rating of 10.0 but ACQ-treated hemlock showed early decay with a mean rating of 9.8. After one year of exposure at Petawawa, the majority of the untreated stakes of both species were moderately decayed. This progressed so that in the fifth year eight spruce and all ten hemlock stakes had failed (Table 5). Similar to the Korean test site, untreated spruce has decayed more rapidly than hemlock. There are no termites present at this test site.

Table 4 Performance of wood in ground contact in Canada

Test	Species	Target retention (kg/m³)	Analysis by FPInnovations		Mean AWPA Rating				
			Retention (kg/m³)	Penetration (mm)	Year 1	Year 2	Year 3	Year 4	Year 5
None	Spruce	none	NA	NA	8.5 (1.4)	6.9 (2.6)	5.4 (2.9)	2.7 (3.5)	1.0 (2.2)
	Hemlock	none	NA	NA	8.9 (0.7)	8.3 (0.8)	6.6 (2.9)	3.1 (3.4)	0.0 (0.0)
CA	Spruce	3.3	3.2 (1.2)	6.6 (3.4)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	9.9 (0.3)	9.5 (1.1)
	Hemlock	3.3	3.0 (0.6)	13.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	9.9 (0.4)	10.0 (0.0)
ACQ	Spruce	6.4	5.5 (1.9)	5.8 (3.3)	10.0 (0.0)	10.0 (0.2)	9.9 (0.3)	9.9 (0.3)	9.3 (0.8)
	Hemlock	6.4	6.8 (0.4)	12.8 (0.6)	10.0 (0.2)	10.0 (0.0)	10.0 (0.0)	9.8 (0.4)	9.8 (0.3)

Standard deviations are shown in parentheses

The decay rate at the Petawawa site may be slightly faster than FPInnovations other two test sites. White spruce treated with 3.3 kg/m^3 CA had average rating of 9.5 at Petawawa at five years compared to 9.9 and 10.0 at Maple Ridge and Kincardine, respectively, after 6 years (Morris and Ingram 2011). White spruce treated with 6.4 kg/m^3 ACQ had average rating of 9.3 at Petawawa at 5 years compared to 9.6 and 9.9 at Maple Ridge and Kincardine, respectively, after six years Untreated white spruce had a rating of 2.7 at year four in Petawawa while the same species had similar ratings at Maple Ridge and Kincardine (2.5 and 2.3 respectively) after six years. The difference is likely partly due to the higher prevalence of soil-inhabiting, strand-forming, wood-rotting basidiomycetes at Petawawa than the other two sites.

Conclusions

Despite penetration and retentions below Canadian and Korean standards, no decay or termite attack was found in CA- or ACQ-treated samples after five years in Korea. Early to moderate decay was found in some of the preservative-treated spruce at the Canadian site, while decay, and particularly termite attack in Korea, was extreme in untreated material.

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FIELD TESTING IN CANADA XXV

PERFORMANCE OF ENGINEERED WOOD PRODUCTS IN ACCELERATED ABOVE-GROUND AND GROUND-CONTACT FIELD TESTS

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Summary

There are a range of applications where engineered wood products (EWP) are used in conditions conducive to decay and where preservative treatment would substantially improve their longevity and reliability, including the exterior of buildings and timber bridges. This paper reports on field performance of glulam and laminated veneer lumber (LVL) treated during or after manufacture.

Glulam and LVL protected by a combination of treatment with borate by two processes plus a film-forming coating were exposed outdoors in an above-ground field test using a modified post and rail test design. The results after eight years' exposure showed that non-pressure borate treatments can preserve coated EWP but would require protection by design. Douglas-fir glulam/LVL have some natural durability and perform well when treated. Black spruce and white spruce glulam plus lodgepole pine and aspen LVL were more difficult to protect. Untreated black-spruce glulam and aspen LVL were highly susceptible to decay

Glulam manufactured by laminating thin lam-stock of three species pre-treated with ACQ-D or CA-B was exposed outdoors in an above-ground field test using a modified post and rail test design, a concrete-contact test simulating a bridge abutment, and in ground contact. The results after five or six years' exposure showed that this material shows promising durability. Material ACQ- or CA-treated to UC 4.1 retentions was sound after six years above ground. Material CA-treated to UC 3.2 retentions was sound after five years in the ground while ACQ-treated material showed signs of decay. Material ACQ-treated to UC 3.2 retentions was sound after five years in concrete contact. Yellow cedar glulam was less durable than glulam made from ACQ-treated lamina. Zinc from galvanized fasteners provided some protection against decay initiation. The γ-joint test provided a very severe above-ground exposure with some decay in two years. The concrete-contact test also provided a very severe above-ground exposure

1 Introduction

Numerous outdoor uses of engineered wood products would substantially benefit from preservative treatment in terms of increased longevity, reliability, and reduced maintenance.

Though undocumented, the authors are aware of many instances of premature decay in glulam under exterior conditions conducive to decay. For glulam used on the exterior of buildings where there is considerable protection by design, pressure treatment with heavy-duty preservatives may be overkill. Under these conditions, surface treatment with a diffusible preservative may be sufficient. For other more exposed applications in critical infrastructure with long design lives, deep penetration with heavy-duty preservatives may be required. This paper reports on field performance of glulam and laminated veneer lumber (LVL) treated during or after manufacture.

The purpose of the first study reported here was to develop decay-resistant glulam and laminated veneer lumber (LVL) for use on the exterior of buildings. The approach was to combine non-pressure borate treatment with an effective transparent coating system. The AWPA has standardized the use of borates for interior construction protected from wetting (AWPA 2014). Borates are diffusible compounds, which can penetrate refractory species (Byrne and Morris 1997), and subsequently migrate to the wet parts of wood. However, their leachability limits their use in exposed exterior applications. One of the strategies to reduce boron leaching in composite materials is coating with varnish or paints (Morris *et al.* 2008).

Although the intended application of these products is for exterior components of buildings with considerable protection by design, to provide rapid results, this test method was designed to be a much more severe exposure. Glulam of four species, and LVL of three species, both untreated and borate-treated using two processes, were included. After application of the coating, the test samples were installed in a long-term above-ground outdoor weathering trial at FPInnovations' Maple Ridge, BC test site in October 2006. A previous report described the test set-up (Morris *et al.* 2007). Due to the anticipated slow progress of decay above ground this material was inspected after four years, then every two years. The present report describes the results of inspections after eight years of exposure.

The purpose of the remaining work reported here was to develop a treated glulam product for use in a range of non-residential applications. These include interior environments susceptible to condensation and decay such as swimming pools and ice arenas, and exterior or semi-exterior uses of glulam in West Coast design. They also include exterior applications such as timber bridges, docks, and other infrastructure. Glulam does not respond well to pressure treatment with water-borne preservatives and oil-type preservatives are not suitable for many applications. The approach taken here was to manufacture glulam from lam-stock pressure treated with waterborne preservatives.

Most Canadian wood species are predominantly heartwood which is not receptive to preservative treatment (Cooper and Morris 2007, Morrell and Morris 2002). However sapwood of lodgepole pine (*Pinus contorta*) affected by the mountain pine beetle is readily separated based on its colour and has increased permeability to preservative treatment (McFarling *et al.* 2006). Red pine (*Pinus resinosa*) has a relatively wide treatable sapwood band and Pacific silver fir (*Abies amabilis*) has relatively permeable heartwood (Morris 1995). Using thin, pure-sapwood lamina of post-MPB lodgepole pine and red pine, and thin lamina of Pacific silver fir was felt to give the best chance of producing a well-treated glulam.

A preliminary study by FPInnovations and sponsored by BC Forestry Innovation Investment (FII) demonstrated that post-MPB thin lamina treated with ACQ could be laminated successfully with phenol-resorcinol-formaldehyde adhesive when used with a resin modifier (Feng and Knudson 2006). Lamination quality without the use of the modifier was not satisfactory. CA-treated material was also successfully bonded. Planing of the treated thin lamina prior to lamination was an essential step for achieving good gluing performance. However, planing of the treated wood represents an additional manufacturing process plus a challenge for disposal of the treated shavings. A further FPInnovations study funded by FII found that the need for planing the treated lamina prior to gluing can be eliminated by smoothing the lumber surface with roller-pressing under ambient conditions, however there was loss of wood strength adjacent to the glueline (Knudson *et al*. 2008, 2009).

An above-ground field test under natural conditions of glulam made from treated thin lamina was initiated by FPInnovations in September 2008 at our field test site in Maple Ridge, BC. Glulam manufactured from three species, both untreated and treated with the two preservatives, ACQ-D and CA-B, were included. Most samples contained some areas of unpenetrated lamina. The previous reports described treatment of the material, manufacture of the glulam, and the test set-up (Knudson *et al.* 2008, 2009). Due to the slow progress of decay above ground this material has been inspected every two years. The present report describes the results of inspections after six years of exposure.

A mill trial was identified as the next logical step towards commercial production of pretreated glulam (Knudson *et al* 2010). As part of this mill trial in 2010, field tests were initiated to investigate the performance, in terms of decay, of preservative-treated glulam beams in both ground-contact and above-ground outdoor exposure. Sections of laminated beams composed of lumber well penetrated with preservative were installed in ground contact, buried vertically to half their length in the ground. Sections of beams composed of lumber not as well penetrated with preservative were installed above ground in contact with masonry blocks (no soil contact). These above-ground samples had one galvanized and one stainless steel bolt inserted vertically in pre-drilled holes in each sample to test the hypothesis that zinc from the sacrificial coating on galvanized bolts would inhibit germination of basidiospores. This report describes the condition of material in these two glulam exposure trials after five years in test

2 Materials and Methods

2.1 Borate-Treated γ-Joint Preparation

Glulam and LVL beams were obtained from the following commercial manufacturers:

LVL
- Aspen from Tembec in Québec

- Douglas-fir from Louisiana Pacific in Golden, BC
- Lodgepole pine from West Fraser in Rocky Mountain House, AB

Glulam
- Black spruce from Nordic Engineered Wood in Québec
- Douglas-fir from Western Archrib in Edmonton, AB
- White spruce from Western Archrib in Edmonton, AB
- Borate-treated lodgepole pine from FPInnovations in Vancouver, BC

The test unit design chosen for this study was a "γ-joint" (Figure 1). This was an enlarged post and rail test unit similar to that used by Amburgey *et al.* (2000) modified with a rebate such that one member is supported by the other without the use of hardware. However, it was found that to prevent dislodging of the arms from the uprights, the top of the arm needed to be secured to the upright with a plastic zap-strap ("tie-wrap"). This configuration was chosen because it provides an excellent water trap as well as exposed horizontal and vertical faces.

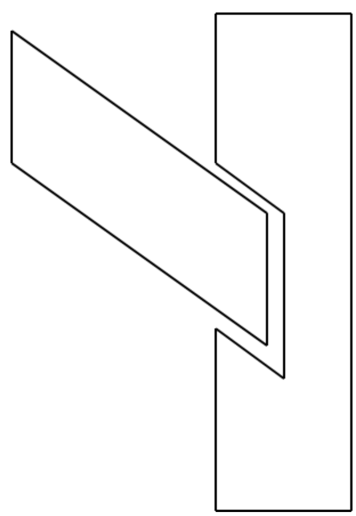

Figure 1 Side view of γ-joint

Because these test pieces were designed to be 100 mm in cross-section, three plies of LVL, which is produced as 40 mm thick beams, had to be glued together. This was completed by the FPInnovations' Engineered Wood Products department in the Vancouver laboratory. The glulam and resulting LVL beams were machined to 100 mm square, and cut to a 425 mm long vertical piece and a 222 mm long slanted arm piece, with rounded edges. There were approximately 60 replicates per material, except for the FPInnovations borate-treated glulam, of which there were only nine. On the vertical member a notched "socket" was cut from the centre of one of the faces parallel to the glueline to a depth of 50 mm at a 45^{o} angle, such that the top and bottom of the notch were each 120 mm from the ends.

One group of approximately 20 units per material was left untreated as controls. A second group of 20 units was dip-treated with a borate/glycol formulation (Boracol 20-2BD, Sansin), containing a quaternary ammonium compound (quat). A third set of 20 γ-joints was borate-treated with a novel proprietary accelerated diffusion process using a buffered amine oxide carrier (Tru-Core®, Kopcoat Inc). This involved dip treatment followed by a diffusion period in a kiln.

All of the γ-joints, both treated and untreated, were brush-coated with two coats of SuperNatural step 1 and one coat of SuperNatural step 2 (Napier). Two bolt holes were drilled out above the arm socket on the upright member of each unit, to be used for attachment to test racks in the field test. Stainless steel identification labels were affixed to the underside of both members of each unit.

Each borate/glycol-treated γ-joint had two fused copper/borate rods (Cobra™Rods, Genics Inc.) inserted in holes drilled out on both members (a total of four rods per γ-joint). These fused copper borate rods, 55 mm in length, are designed to dissolve when moisture is encountered in service to allow the preservative to diffuse into the wood, thus providing protection from decay. One rod was put 20-30 mm both above and below the notch on the right-hand side of each vertical member, and two were put 25 mm from each edge at the centre of the lower face of each angle piece. The holes were plugged with ACQ-treated wood plugs, and the plugs were covered with silicone (Figure 2).

In addition to the above, glulam made from borate-treated lamina of lodgepole pine from a previous study (Feng and Anderson 2004) were also cut into γ-joints, coated and installed in test.

Figure 2 Borate/glycol-treated γ-joint showing copper/borate rod locations

Several replicates per material/treatment were retained at the lab as unexposed reference pieces to be analyzed for borate content in the future for comparison with exposed samples which would be sacrificed for analysis. This analysis was done after seven years in test (Morris *et al.* 2014). The remainder were installed in the field test.

2.2 ACQ- and CA-Treated Sample Preparation

2.2.1 γ-Joints

Glulam sections were obtained from stock retained from previous FPInnovations studies (Knudson *et al.* 2008, 2009). Three species: post-MPB lodgepole pine, coastal Pacific silver fir, and sapwood of red pine were treated with either alkaline copper quat, type D (ACQ-D) or copper azole type B (CA-B). The test unit design chosen for this study was also the "γ-joint" (Figure 1).

Glulam beams, 89 x 89 mm in cross-section, were cut to 425 mm in length to form the upright member of the γ-joint, and additional pieces were cut on the diagonal, 320 mm in length, to form the "arm" portion of the joint. On the vertical member, a notched "socket" was cut from the centre of one of the faces parallel to the glue line to a depth of 50 mm at a 45^o angle. A 2 mm gap was provided where the arm fitted into the upright to allow for expansion. The uprights were drilled to accommodate two bolts for fastening the experimental unit to the test racks. Ten replicates were prepared for the ACQ- and CA-treated material, with six replicates for the untreated control material. The uprights and angled arms of each unit were both identified with a numbered stainless steel tag.

2.2.2 Ground-Contact Test

Glulam sections (five-ply) were obtained from stock retained from a previous FPInnovations study (Knudson *et al* 2009a, 2009b). The treated material was chosen because it had generally high levels of preservative penetration. However, replication was limited by the available material. Beams were left untreated or treated with ACQ-D or CA-B.

Each beam section was crosscut to one 66 cm in length test "post" and one 10 cm reference piece. The reference pieces were retained for possible future analysis. Both cut ends of the 66 cm posts were given two brush coats of 2% copper naphthenate, and stainless steel labels were applied to each sample.

Unexposed pieces which had been retained at the laboratory for five years since the study was initiated were analyzed in 2015 for penetration and retention. Cores, 9 mm in diameter, were removed from the two outer and the central ply of each beam, and cut to 13 mm in length. The cores were split longitudinally, and the preservative penetration was measured on one half-core. The other halves from all the cores per species/treatment group were combined as one sample, and ground to sawdust, which was analyzed for copper using ICP. Using the specific gravity of each species, the copper content was converted to kg/m^3 of ACQ-D or copper azole.

2.2.3 Glulam Beams Above Ground (on masonry blocks)

Sections of 12-ply beams were obtained from stock retained from a previous FPInnovations study. Beams were untreated or treated with ACQ-D. This material was selected for above-ground testing because it contained substantial zones of untreated wood. In the case of the post-MPB lodgepole pine this was due to a high proportion of untreatable heartwood in this batch of material. The reason for the lower penetration in the Pacific silver fir in this study is unknown. Replication was limited by the available material. Untreated yellow cedar glulam was included as reference material, since this naturally durable material is being used untreated for bridge timbers in British Columbia.

Each beam section was crosscut to one 39 cm length and one 15 cm reference piece. The reference piece was retained for possible future analysis. Both cut ends of each 39 cm sample were given two brush coats of 2% copper naphthenate. Each section was drilled completely through at two locations on the narrow face to accommodate bolts. The two bolt holes were located at two of the four intersections one-third the distance from the ends and one-third the distance from the edges, such that the holes were staggered on the faces as shown in Figure 3.

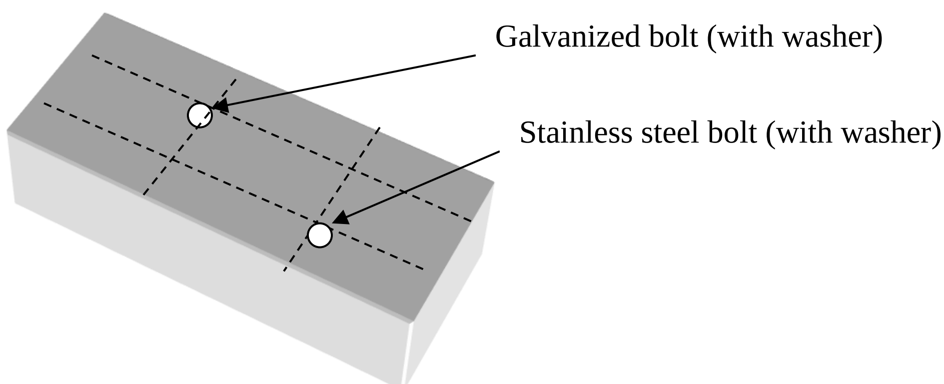

Figure 3 Bolt locations staggered at one–third distance in length and width dimensions in above- ground test samples

Unexposed sections of the beams were analyzed for preservative penetration and retention after five years in storage, as described above for the ground-contact samples. Lamina nos. 1, 5, 8, and 12 (out of the 12 lamina on each piece) were sampled on these above-ground beams.

2.3 Test Site

The test site at Maple Ridge, BC is located within the University of BC Malcolm Knapp Research Forest. The area is a clearing in second growth coastal western hemlock forest but has been a grass field for decades. It was previously used as a deer pen. The soil is a sandy silt loam to a depth of 0.3 m. It has a pH around 5.1 and is relatively high in organic matter (15 - 21%). Below this is a layer of fine- to coarse-grained sand with some gravel and silt. In summer, groundwater is between 0.5 and 2.4 m below grade and flows in a predominantly southwest direction. During the winter months, the groundwater reaches the surface at the southwest end of the site. This site has a rainfall of over 2150 mm per year and an average yearly temperature of 9.6°C with mean daily maximum and minimum temperatures of 6°C and 1°C in January, and 23°C and 12°C in July. It falls within the moderate decay hazard zone for outdoor above-ground exposure using Scheffer's climate index (Scheffer 1971; Setliff 1986), with an updated Scheffer index (SI) of 63 based on 30-year climate normal data (Morris and Wang 2008). The calculated Scheffer Index for the recent 10-year test period (SI_t) was 56. The moderate decay hazard zone includes most of the major population centres of North America. Soil-inhabiting wood-rotting basidiomycetes including *Leucogyrophana pinastri* (Fries) Ginns & Weresub, *Fibroporia vaillantii* (DC.) Parmasto, *Antrodia serialis* Ryvarden & Gilb. and *Tapinella* sp. are found on test material sporadically across the entire site.

2.4 Test Unit Installation

The two pieces of the borate-treated γ-joints were put together, then the upright member was attached using stainless steel bolts to a yellow cedar exposure fence in a randomized array at FPInnovations' test site at Maple Ridge in September 2006, such that the samples were held approximately 1.5 metres above ground level, facing south. Their locations were mapped. Similarly, the ACQ- and CA-treated γ-joints were installed in September 2008.

The glulam posts were installed at FPInnovations' test site at Maple Ridge, BC in April 2010, buried vertically to half their length (Figure 4), with samples representing the test variables randomly located among the four quadrants of this test site to offset variations in soil conditions within the Maple Ridge plot. Post holes were pre-drilled using a six-inch diameter powered auger and a sample layout map was prepared.

Figure 4 Glulam posts buried vertically to half depth in the ground

For the above-ground study of glulam beams on masonry blocks, one galvanized and one stainless steel bolt, with matching washers, were placed into the two holes at the time of installation. The bolts were dropped into the holes but did not protrude through the samples and were not fastened. The samples were placed on masonry blocks with the bottom face of the sample and both ends in contact with the blocks to promote retention of moisture at the contact surfaces (Figure 5). Stainless steel labels were applied to the samples and the samples were installed at FPInnovations' Maple Ridge test site in April 2010.

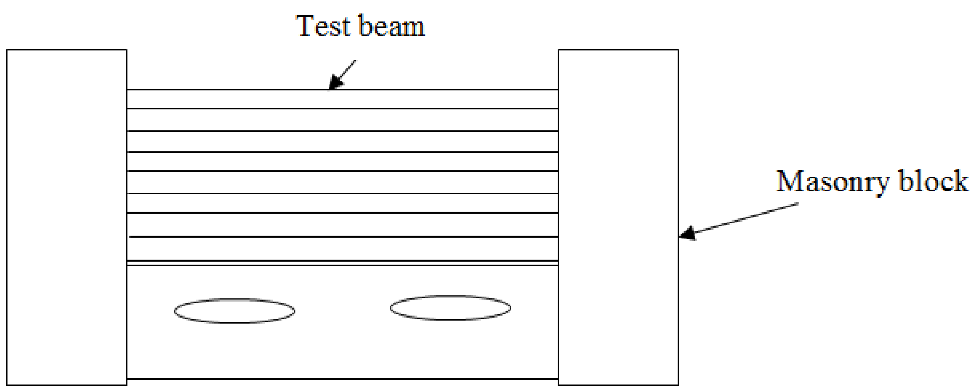

Figure 5 Beam sections exposure above ground on and between masonry blocks

2.5 Inspection of Test Material

Due to the relatively slow progress of decay above ground the borate-treated test units were first inspected for decay after four years in test, then on a 2-year cycle. The ACQ- and CA-treated units were inspected every two years. Each was examined visually for indications of decay such as the presence of fungal mycelium or discolouration at six locations: the horizontal top and bottom of the upright, around the bolt holes, the inner vertical surface of the joint on both the upright and angled piece, and the outer vertical end of the angled piece. If decay was suspected, the area of interest was gently probed with a metal scraper. Each surface was then assigned a decay rating, based on the AWPA E7 (2008) grading system (Table 1).

A rating of 9.5 was given when mycelium with the appearance of wood-rotting basidiomycetes was seen on the wood surface but no softening was detected. The presence of a fruitbody would generate an automatic rating of no higher than 8 on the basis that the fungus must have degraded a substantial volume of wood to produce the fruitbody.

Table 1 AWPA rating system

Decay Rating	Condition	Description
10	Sound	No sign or evidence of decay, wood softening, or discoloration caused by microorganism attack.
9.5	Trace-suspect	Some areas of discolouration and/or softening associated with superficial microorganism attack.
9	Slight attack	Decay and wood softening is present. Up to 3% of the cross sectional area affected.
8	Moderate attack	Similar to "9" but more extensive attack with 3-10% of cross sectional area affected.
7	Moderate/severe attack	Sample has between 10-30% of cross sectional area decayed.
6	Severe attack	Sample has between 30-50% of cross sectional area decayed.
4	Very severe attack	Sample has between 50-75% of cross sectional area decayed.
0	Failure	Sample has functionally failed. It can either be broken by hand due to decay, or the evaluation probe can penetrate through the sample.

Annually since installation, in August or September, each glulam stake was removed from the soil, loose grass and dirt were brushed off, and it was examined visually for indications of decay such as the presence of fungal mycelium or discolouration. If decay was suspected, the area of interest was gently probed with a metal spatula. Each specimen was then assigned a rating for decay, based on the AWPA E7 grading system.

After five years of exposure, each above-ground beam was removed from the masonry block, examined visually for indications of decay, as described above, and assigned a decay rating at six locations: on the top surface, bottom surface, the end closest to the stainless steel bolt, the end closest to the galvanized bolt, and inside each of the two bolt holes. A screwdriver specially adapted with a bent end was used to probe inside the bolt holes for softness associated with decay (Figure 6).

Figure 6 Inspecting above-ground beams

3 Results and Discussion

3.1 Borate-Treated γ-Joints

Tables 2–3 summarize the mean decay ratings for each treatment over the eight years of study, and the percentage of boards with at least one inspected surface with confirmed decay (rated 9 or less) at eight years.

Decay, where present, was found most commonly inside the joint, on the vertical faces of the upright and angled members, due to the effect of slow drying. Some decay was also noted on the horizontal top end of the vertical member, due to exposure of the end-grain. The bolt holes and the outer vertical face of the angled member were not decayed, with the exception of untreated black spruce glulam and aspen LVL. These results confirm that the novel test method being used in this experiment is an effective technique to accelerate above-ground decay.

Figure 7 Failure of untreated black spruce glulam unit at six years of exposure

The most fungal attack, with decay noted in about 25% of samples after four years, was found in untreated black spruce glulam and untreated aspen LVL. This decay advanced to one failed (defined as one surface rated 0) black spruce glulam unit after six years (Figure 7), and one failed aspen LVL control after eight years. At the eight-year inspection, decay was found in 54% of the black spruce glulam units and 83% of the aspen LVL.

While less than in black spruce glulam and aspen LVL, some decay was found in all groups of untreated glulam and LVL after eight years in test (Tables 2 and 3). Although these units were not refinished during the exposure period, these results suggest that coating alone may not provide adequate long-term protection from decay above ground.

In contrast to the untreated material, little decay was detected in groups which received treatment with borate applied by either method up to six years of monitoring, and greatly reduced decay at eight years. In the very decay susceptible aspen, even with borate treatment, almost 30% of the LVL units contained early decay at eight years (Table 3).

Table 2 Decay ratings in borate-treated glulam

Year	Preservative	Decay ratings: Vertical Top End	Vertical Bottom End	Vertical Inside Joint	Bolt Holes	Angle Inner End	Angle Outer End	% of Samples rated ≤ 9
4	Douglas-fir glulam – untreated	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	0
6	Douglas-fir glulam – untreated	9.8 (0.6)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	8
8	Douglas-fir glulam – untreated	9.8 (0.6)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.1)	10.0 (0.1)	8
4	Douglas-fir glulam – Borate in buffered amine oxide	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	0
6	Douglas-fir glulam – Borate in buffered amine oxide	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	0
8	Douglas-fir glulam – Borate in buffered amine oxide	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	0
4	Douglas-fir glulam – Borate/glycol/rods	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	0
6	Douglas-fir glulam – Borate/glycol/rods	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	0
8	Douglas-fir glulam – Borate/glycol/rods	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	0
4	Black spruce glulam – untreated	9.8 (0.6)	10.0 (0.0)	9.8 (0.6)	9.9 (0.3)	9.9 (0.3)	10.0 (0.0)	23
6	Black spruce glulam – untreated	9.2 (2.8)	10.0 (0.0)	9.1 (2.8)	9.2 (2.8)	9.9 (0.3)	9.8 (0.6)	23
8	Black spruce glulam – untreated	9.1 (2.7)	10.0 (0.0)	9.0 (2.7)	9.2 (2.8)	9.6 (0.6)	9.8 (0.6)	54
4	Black spruce glulam – Borate in buffered amine oxide	10.0 (0.0)	10.0 (0.0)	9.9 (0.2)	10.0 (0.0)	9.9 (0.2)	10.0 (0.0)	0
6	Black spruce glulam – Borate in buffered amine oxide	10.0 (0.0)	10.0 (0.0)	9.9 (0.3)	10.0 (0.0)	9.9 (0.2)	10.0 (0.0)	8
8	Black spruce glulam – Borate in buffered amine oxide	9.8 (0.3)	10.0 (0.0)	9.8 (0.4)	10.0 (0.0)	9.9 (0.2)	10.0 (0.1)	15
4	Black spruce glulam – Borate/glycol/rods	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.1)	10.0 (0.0)	0
6	Black spruce glulam – Borate/glycol/rods	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	9.9 (0.3)	10.0 (0.0)	8
8	Black spruce glulam – Borate/glycol/rods	9.9 (0.2)	10.0 (0.0)	10.0 (0.1)	10.0 (0.0)	10.0 (0.0)	9.8 (0.8)	8
4	Lodgepole pine glulam – borate treated lamina	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	0
6	Lodgepole pine glulam – borate-treated lamina	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	0
8	Lodgepole pine glulam – borate-treated lamina	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	0
4	White spruce glulam – untreated	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	9.9 (0.3)	10.0 (0.0)	8
6	White spruce glulam – untreated	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	9.8 (0.6)	10.0 (0.0)	8
8	White spruce glulam – untreated	9.8 (0.6)	10.0 (0.0)	9.7 (1.2)	10.0 (0.0)	9.8 (0.6)	10.0 (0.0)	17

4	White spruce glulam – Borate in buffered amine oxide	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	0
6	White spruce glulam – Borate in buffered amine oxide	10.0 (0.1)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	0
8	White spruce glulam – Borate in buffered amine oxide	9.9 (0.3)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	9.6 (0.8)	10.0 (0.0)	25
4	White spruce glulam – Borate/glycol/rods	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	0
6	White spruce glulam – Borate/glycol/rods	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	0
8	White spruce glulam – Borate/glycol/rods	9.8 (0.3)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	9.9 (0.4)	10.0 (0.0)	14

Standard deviations given in parentheses

Table 3 Decay ratings in borate-treated LVL

Year	Preservative	Decay ratings						% of Samples rated ≤ 9
		Vertical Top End	Vertical Bottom End	Vertical Inside Joint	Bolt Holes	Angle Inner End	Angle Outer End	
4	Douglas-fir LVL – untreated	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	0
6	Douglas-fir LVL – untreated	10.0 (0.0)	10.0 (0.0)	9.9 (0.3)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	8
8	Douglas-fir LVL – untreated	10.0 (0.0)	10.0 (0.0)	9.9 (0.3)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	8
4	Douglas-fir LVL – Borate in buffered amine oxide	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	0
6	Douglas-fir LVL – Borate in buffered amine oxide	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	0
8	Douglas-fir LVL – Borate in buffered amine oxide	9.9 (0.2)	10.0 (0.0)	10.0 (0.1)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	5
4	Douglas-fir LVL – Borate/glycol/rods	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	0
6	Douglas-fir LVL – Borate/glycol/rods	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	0
8	Douglas-fir LVL – Borate/glycol/rods	9.9 (0.2)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	0
4	Lodgepole pine LVL – untreated	10.0 (0.0)	10.0 (0.0)	10.0 (0.1)	10.0 (0.0)	10.0 (0.1)	10.0 (0.0)	0
6	Lodgepole pine LVL – untreated	10.0 (0.0)	10.0 (0.0)	9.8 (0.6)	10.0 (0.0)	9.9 (0.2)	10.0 (0.0)	8
8	Lodgepole pine LVL – untreated	9.9 (0.2)	10.0 (0.0)	9.2 (2.9)	10.0 (0.0)	9.1 (2.9)	10.0 (0.0)	16
4	Lodgepole pine LVL – Borate in buffered amine oxide	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	0
6	Lodgepole pine LVL – Borate in buffered amine oxide	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	0
8	Lodgepole pine LVL – Borate in buffered amine oxide	9.8 (0.6)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	15
4	Lodgepole pine LVL – Borate/glycol/rods	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	0
6	Lodgepole pine LVL – Borate/glycol/rods	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	0
8	Lodgepole pine LVL – Borate/glycol/rods	9.9 (0.2)	10.0 (0.0)	10.0 (0.1)	10.0 (0.0)	9.9 (0.2)	10.0 (0.0)	5

4	Aspen LVL – untreated	9.8 (0.6)	10.0 (0.0)	9.8 (0.6)	9.8 (0.6)	9.5 (0.8)	10.0 (0.0)	25
6	Aspen LVL – untreated	9.8 (0.6)	10.0 (0.0)	9.2 (1.2)	10.0 (0.0)	9.2 (1.0)	10.0 (0.0)	67
8	Aspen LVL – untreated	9.1 (1.2)	10.0 (0.0)	7.7 (2.7)	10.0 (0.0)	8.3 (1.3)	9.9 (0.3)	83
4	Aspen LVL – Borate in buffered amine oxide	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	0
6	Aspen LVL – Borate in buffered amine oxide	10.0 (0.0)	10.0 (0.0)	9.9 (0.2)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	5
8	Aspen LVL – Borate in buffered amine oxide	9.9 (0.3)	10.0 (0.0)	9.9 (0.3)	10.0 (0.0)	9.8 (0.4)	10.0 (0.0)	28
4	Aspen LVL – Borate/glycol/rods	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	0
6	Aspen LVL – Borate/glycol/rods	10.0 (0.1)	10.0 (0.0)	10.0 (0.1)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	0
8	Aspen LVL – Borate/glycol/rods	9.9 (0.2)	10.0 (0.0)	9.8 (0.4)	10.0 (0.0)	9.8 (0.5)	10.0 (0.0)	29

Standard deviations given in parentheses

3.2 ACQ- and CA-Treated γ-Joints

Table 4 summarizes the mean decay ratings for each treatment over the six years of study, and the percentage of boards with at least one inspected surface with confirmed decay (rated 9 or less) at six years.

Decay, where present, was found generally inside the joint, on the vertical faces of the upright and angled members, due to the effect of slow drying (Figure 8). Some decay was also noted on the horizontal top end of the vertical member, due to exposure of the end-grain. This confirms the importance of the application of field-cut preservatives (AWPA M4). The bolt holes and the outer vertical face of the angled member were not decayed, with the exception of one untreated lodgepole pine sample rated 9.5 on the outer vertical face of the angle at six years.

Early decay was noted in one untreated Pacific silver fir control after only two years. At the six-year inspection, two out of the six untreated Pacific silver fir control units contained moderate or advanced decay, with one unit having failed (defined as one surface rated 0). Although no decay had been detected at the two- and four-year inspections of the red pine controls, after six years in test five of six test units had surfaces rated 8 or less, with the remaining unit containing surfaces rated 9. One untreated lodgepole pine control had two surfaces rated 9 at the six-year evaluation.

These results confirm that the novel test method being used in this experiment is an effective technique to accelerate above-ground decay. However, the degree of acceleration is not known.

In contrast to the untreated material, no decay was detected in groups which received treatment with either ACQ-D or CA over the six years of monitoring.

Figure 8 Decay after six years in untreated glulam γ-joint installed above ground

Table 4 Decay ratings in ACQ- and CA-treated γ-joints

Year	Preservative	Decay ratings						% of Samples Rated ≤ 9
		Vertical Top End	**Vertical Bottom End**	**Vertical Inside Joint**	**Bolt Holes**	**Angle Inner End**	**Angle Outer End**	
2	Lodgepole pine – untreated	9.8 (0.3)	10.0 (0.0)	9.9 (0.2)	10.0 (0.0)	9.9 (0.2)	10.0 (0.0)	0
4	Lodgepole pine – untreated	9.8 (0.3)	10.0 (0.0)	9.8 (0.3)	10.0 (0.0)	9.8 (0.3)	10.0 (0.0)	0
6	Lodgepole pine – untreated	9.7 (0.3)	10.0 (0.0)	9.6 (0.4)	10.0 (0.0)	9.6 (0.4)	9.9 (0.2)	20
2	Lodgepole pine – CA-treated	10.0 (0.0)	10.0 (0.0)	10.0 (0.2)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	0
4	Lodgepole pine – CA-treated	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	0
6	Lodgepole pine – CA-treated	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	0
2	Lodgepole pine – ACQ-treated	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	0
4	Lodgepole pine – ACQ-treated	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	0
6	Lodgepole pine – ACQ-treated	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	0
2	Pacific silver fir – untreated	9.9 0.2	10.0 0.0	9.8 0.4	10.0 0.0	9.8 0.4	10.0 0.0	16
4	Pacific silver fir – untreated	9.9 0.2	10.0 0.0	8.8 2.4	10.0 0.0	8.9 2.4	10.0 0.0	33
6	Pacific silver fir – untreated	9.5 0.4	10.0 0.0	7.8 3.9	10.0 0.0	8.1 4.0	10.0 0.0	66
2	Pacific silver fir – CA-treated	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	0
4	Pacific silver fir – CA-treated	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	0
6	Pacific silver fir – CA-treated	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	0
2	Pacific silver fir – ACQ-treated	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	0
4	Pacific silver fir – ACQ-treated	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	0
6	Pacific silver fir – ACQ-treated	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	0
2	Red pine – untreated	9.8 0.3	10.0 0.0	9.7 0.3	10.0 0.0	10.0 0.0	10.0 0.0	0
4	Red pine – untreated	9.9 0.2	10.0 0.0	9.8 0.3	10.0 0.0	9.8 0.3	10.0 0.0	0
6	Red pine – untreated	9.4 0.7	9.3 1.0	8.3 0.8	10.0 0.0	8.8 0.7	10.0 0.0	100
2	Red pine – CA-treated	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	0
4	Red pine – CA-treated	10.0	10.0	10.0	10.0	10.0	10.0	0

		(0.0)	(0.0)	(0.0)	(0.0)	(0.0)	(0.0)	
6	Red pine – CA-treated	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	0
2	Red pine – ACQ-treated	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	0
4	Red pine – ACQ-treated	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	0
6	Red pine – ACQ-treated	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	0

Standard deviations given in parentheses

3.3 Ground-Contact Test

The CSA penetration requirement specified for these samples (use category UC4.1) is 80% meeting 10 mm, and the specified retention is 6.4 kg/m³ for ACQ-D and 3.3 kg/m³ for copper azole (Canadian Standards Association 2015). Only red pine met the penetration requirement (Table 5). The material in this study was treated to above-ground loadings, consequently it does not meet the retention requirements.

Preservative-treated glulam in ground contact remained in excellent condition after five years in test (Table 5). Copper azole-treated specimens were completely sound (all rated 10) while some early decay (ratings of 9) were found in ACQ-D-treated material. In contrast, moderate to severe decay was found after five years in the untreated controls of all three species.

Table 5 Glulam stakes in ground contact

Species	Treatment	Retention (kg/m³)	Penetration (mm)	%≥10 mm	Decay after 5 years	% of samples rated ≤9
Pacific silver fir	None	NA	NA	NA	5.5 (2.1)[1]	100
	ACQ-D	4.5	17 (5)	84	9.5 (0.5)	50
	CA	2.0	13 (7)	67	10.0 (0.0)	0
Lodgepole pine	None	NA	NA	NA	8.5 (0.7)	100
	ACQ-D	5.0	11 (7)	53	9.5 (0.5)	40
	CA	2.6	13 (7)	72	10.0 (0.0)	0
Red pine	None	NA	NA	NA	7.5 (0.7)	100
	ACQ-D	4.5	18 (3)	94	9.8 (0.4)	16
	CA	2.3	16 (5)	89	10.0 (0.0)	0

[1] Standard deviations shown in parentheses; NA: not applicable

3.4 Glulam Beams Above Ground (on masonry blocks)

The CSA penetration requirement specified for these samples (use category UC3.2) is 80% meeting 10 mm, and the specified retention is 4.0 kg/m³ for ACQ-D. Assay results given in Table 6 show that this material met the specified retention in Pacific silver fir and was close to the requirement in lodgepole pine. Preservative penetration failed to meet the standard in both species.

Table 6 Assay of ACQ-D-treated above-ground glulam beams

Species	ACQ retention (kg/m³)	Penetration (mm)	%≥10 mm
Pacific silver fir	4.2	9 (5)[1]	55
Lodgepole pine	3.7	7 (6)	65

[1] Standard deviations shown in parentheses

No confirmed decay was found in any of the ACQ-D-treated beams of both lodgepole pine and Pacific silver fir exposed above ground (Table 7). One bolt hole in lodgepole pine was rated 9.5 for a suspicion of softening. It was noted that in these specimens the galvanized bolt showed some rust (not quantified) while the stainless steel bolt was in perfect condition (Figure 9).

Table 7 Glulam beams above ground

Species	Treatment	Mean decay ratings at 5 years						% of samples with a rating of 9 or less
		Top	Bottom	End with Galvanized Bolt	End with Stainless Bolt	Bolt Hole, Galvanized	Bolt Hole Stainless	
Pacific silver fir	None	9.1 (1.2)[1]	7.8 (3.3)	6.6 (2.7)	6.5 (1.2)	9.6 (0.7)	8.6 (0.5)	100
	ACQ-D	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	0
Lodgepole pine	None	9.7 (0.7)	9.4 (0.5)	7.8 (0.9)	7.0 (1.3)	10.0 (0.0)	9.6 (0.7)	100
	ACQ-D	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	10.0 (0.0)	9.9 (0.2)	0
Yellow cedar	None	10.0 (0.0)	9.6 (0.5)	9.4 (0.7)	9.4 (0.7)	10.0 (0.0)	10.0 (0.0)	67

[1] Standard deviations shown in parentheses

Figure 9 Rust on galvanized bolt in an ACQ-treated sample

In contrast, the untreated beams showed moderate to severe decay (ratings around 7.0) at the ends in contact with the masonry blocks. Fruitbodies of *Gloeophyllum sepiarium* were noted on several beams of both of the non-durable species. This is the fungus most commonly found decaying wood above ground in Canada (Morris 1999). In both of the non-durable species, decay was notably inhibited in untreated material in the vicinity of the galvanized bolt when compared to the stainless bolt (Figures 10 – 11). In untreated Pacific silver fir, where decay was the most advanced of the three species (12), decay was detected inside the stainless steel bolt hole in all eight beams, but in only two out of the eight galvanized bolt holes. This supports the hypothesis that zinc from the sacrificial coating on galvanized bolts will inhibit germination of basidiospores.

Somewhat surprisingly, considering its natural durability and good performance as decking (Morris *et al.* 2016), untreated yellow cedar beams showed early signs of decay at the ends in contact with the masonry blocks. This confirmed that naturally durable species cannot be considered as a direct substitute for preservative-treated wood.

Figure 10 Fruitbodies of *Gloeophyllum sepiarium* on the top surface of an untreated Pacific silver fir glulam beam close to the stainless steel bolt.

Figure 11 Fruitbodies of *Gloeophyllum sepiarium* towards the end of an untreated lodgepole pine beam with the stainless steel bolt

Figure 12 More extensive mycelial growth on the underside of an untreated Pacific silver fir glulam beam at the end with the stainless steel bolt.

Where decay was found in the above-ground test material, it was most severe at the ends in contact with the masonry block, confirming that this is an effective water trap. This location of the test design was intended to simulate a poorly designed bridge where the end of the glulam could be in direct contact with a concrete abutment with no waterproofing or preservative-treated bearing plate. In most cases the soil level had risen during the five years of exposure to the top of the masonry block underneath the glulam beams, and in a few cases soil had percolated between the beam and the block. This also simulates a worst case, but realistic, scenario for bridge timbers designed as above-ground components.

4 Conclusions

- Non-pressure borate treatments can preserve coated EWP but would also require protection by design
- Douglas-fir glulam/LVL have some natural durability and perform well when treated
- Black spruce and white spruce glulam plus lodgepole pine and aspen LVL are more difficult to protect
- Untreated black-spruce glulam and aspen LVL are highly susceptible to decay
- Glulam of thin lamina treated with waterborne preservatives appears highly promising.

    - Material ACQ- or CA-treated to UC 4.1 retentions was sound after six years above ground
    - Material CA-treated to UC 3.2 retentions was sound after five years in ground. ACQ-treated material showed signs of decay
    - Material ACQ-treated to UC 3.2 retentions was sound after five years in concrete contact
- Yellow cedar glulam is less durable than glulam made from ACQ-treated lamina
- Zinc from galvanized fasteners can provide some protection against decay initiation
- The γ-joint test provided a very severe above-ground exposure – some decay in two years
- The concrete-contact test also provided a very severe above-ground exposure

5 Acknowledgements

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PERFORMANCE OF NON-TRADITIONAL COATED PRODUCTS AGAINST FUNGAL AND TERMITE ATTACK UNDER SUB-TROPICAL CONDITIONS: 30 MONTH REPORT

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Summary

A variety of alternative, spray or short term dip-applied wood treatments have recently entered the market as alternatives to traditional preservative treated wood. Surface treatments are part of the building codes in Australasia, but these treatments are used in applications that are fully protected from wetting and are primarily used for insect protection. the North American systems are purported to be useful in exterior, above ground exposures. However, there is little public comparative data on the performance of these newer systems. In this report, we describe decay and termite tests of several products including Timbersil, Eco Red Shield, and BluWood in comparison with non-treated Douglas-fir lumber as well as wood treated with copper azole. Termite tests indicated that Eco Red Shield and BluWood provided little protection against formosan termites, while Timbersil performed well but not as well as copper azole treated wood. Decay tests are still in the early stages, but visible decay was present on wood treated with either Eco Red Shield or BluWood and exposed above the ground. The results suggest that caution should be exercised when contemplating the use of these products in areas with high termite pressure or where wetting can occur.

Keywords: Copper azole, Douglas-fir, Boron, Timbersil, Eco Red Shield, BluWood

1. Introduction

Pressure treatment with wood preservatives has long been recognized as an excellent method for prolonging the useful life of wood used under adverse conditions (Hunt and Garratt, 1967). Treatments can extend the useful life of a product ten times or longer than a similar piece of non-treated material. While these products have performed well and are widely used in North America, many consumers are concerned about the use of biocides in a variety of materials, including wood. These concerns have created markets for alternative products. The most frequently used substitutes for treated wood are the wood plastic composites, which claim to be durable and maintenance free. However, these products are also far more costly, limiting them to a higher end market niche.

A number of other non-biocidal products have been developed in Europe, including thermally modified wood and acetylated wood. Acetylated wood has performed well in a variety of exposures, but it has generally not fared well in North America because of cost. Thermally modified wood lacks the resistance to decay required for many treated wood applications in North America and is not widely available. Both of these products are also more costly than treated wood.

The lack of effective alternatives to treated wood has encouraged the development of substitute products. Among these are products pressure treated with silicates as well as products that are surface coated with products claiming to be non-biocidal but generally containing small amounts of borates. These products have typically been standardized for use through the International Code Council Evaluation Service.

Most of these products have approvals for specific applications such as the American Wood Protection Association Use Categories UC1, 2, or 3A and, in many cases, should perform well in these exposures. However, many of these products also tend to extend their claims to products far outside their initial uses, often with little or no supporting data. For example, the website for the producer of silicate impregnated products contained images of railroad ties, a UC4 application and some manufacturers of spray on treatments suggest that their products will perform under UC3B conditions where regular wetting is likely.

The lack of publically available data on the performance of these products makes it difficult for purchasers to determine which products will actually perform as promised. This creates confusion in the market place and, if these products do not perform as claimed, creates a negative image of all treated wood products. There is a critical need for comparative data to determine if these products are suitable for the exposures claimed.

Developing data on the performance of these materials in relation to both non-treated wood and wood pressure-treated with a conventional preservative for the same application would help consumers make informed choices about materials for above ground, exterior exposures.

The goal of this project was to evaluate the performance of wood products coated with various materials and exposed at sites in Corvallis, Oregon and Hilo, Hawaii. The Hilo site was employed because it can take considerable time periods for decay to occur out of direct soil contact in more temperate climates. This report summarizes the inspection of the samples in Hawaii after 30 months of exposure.

2. Materials and Methods

All materials in this test were commercially treated and provided as nominal 2x4 lumber that was then cut to lengths appropriate for each test method (Table 1). Samples were also retained for later examination. Samples were set out at two time points. The samples treated with BluWood, Eco Red Shield (I), and copper azole along with non-treated controls were exposed in November 2013 (Table 1). In June 2015, additional samples consisting of new, non-treated Douglas-fir lumber, a newer version of Eco Red Shield (II), and HiBor borate treated wood were placed on the sites.

The lumber was cut to the appropriate size for each test configuration. The dimension lumber necessitated the use of larger dimensions for each test. All of the cut ends were dipped for 30 seconds in a solution of 4.8% pentachlorophenol in diesel oil for the first set or 2% copper naphthenate (as Cu) in diesel oil for the second. The samples were dipped to protect the potentially untreated ends exposed by cutting. This was essential since most of the tested treatments are reported to function as barriers.

Samples were exposed in test sites at Hilo, Hawaii or Corvallis, Oregon. The Hilo site receives over 5 m of rainfall per year and has average daytime temperatures between 24 and 28 C, while the Corvallis site receives approximately 1.4 m of rainfall per year and has daytime temperatures that range from 4 to 27 C, depending on the time of year. The risk of decay at the Hilo site is described as extreme, while that at Corvallis is considered moderate. The Scheffer Climate indices for the two sites are approximately 45 and 280, respectively, where 0 is no decay (Scheffer, 1971).

Table 1. Treatments evaluated for decay and termite resistance in above ground exposures at sites located in Corvallis, Oregon or Hilo, Hawaii.

Treatment	**Source**	**Wood Species**	**Number of Samples Exposed/Site**		
			E18 Termite GP	**E26 Decay GP**	**Sandwich Test**
None	Home Depot	Douglas-fir	15	35	10
TimberSil	TimberSil Wood Products, Springfield, VA	Southern pine	15	35	10
Eco Red Shield I	Eco Building Products Inc., Vista, CA	Douglas-fir	15	35	10
BluWood	Conrad Wood Preserving, Coos Bay, OR	Douglas-fir	15	35	10
Copper Azole	Exterior Wood, Inc., Washougal, WA	Douglas-fir	15	35	10
Eco Red Shield II*	Eco Building Products Inc., Vista, CA	Hem-Fir	10	10	10
HiBor*	Royal Pacific Wood Preserving, McMinnville, OR	Douglas-fir	10	10	10

*** Added to test sites, June 2015**

The materials were tested in three configurations. Resistance to attack by Formosan termites was evaluated using a modification of AWPA Standard E26. Briefly, hollow concrete blocks were placed on the soil. Pine sapwood stakes were driven into the ground within the hollow blocks to attract termites, then the wood test blocks (nominal 50 by 100 by 125 mm long) were placed on the concrete blocks in between non-treated wood that serves as a feeder material for the workers to explore (Figure 1).

The blocks were then covered with a water shedding cap that produced a dry, non-soil contact exposure equivalent to a Use Category 1 or 2 exposure. It is important to note that this test does not expose the wood to any rainfall and, as a result, there is little or no potential for leaching of any active ingredients from the blocks.

Formosan termites are extremely aggressive and untreated wood at the Hilo test site is typically destroyed within six months of installation. The control and test samples were evaluated at six-month intervals for degree of termite attack on a scale from 10 (no attack) to 0 (failure). Fifteen blocks were tested for each treatment and the test was evaluated after 7, 12 or 18 months of exposure.

Resistance to decay in a UC3B-type exposure was evaluated in two above ground tests. In the first test, 125 mm long blocks were cut and placed on concrete blocks following the procedures described in AWPA Standard E18. The samples were then covered with a mesh screen that allowed water to strike the blocks but limited drying.

Thirty-five blocks were installed for each treatment. Block condition was visually assessed at six-month intervals on a scale from 10 (sound, no decay) to 0 (completely decayed). Selected samples will be removed at intervals to determine residual chemical content (where appropriate) as well as the presence of internal fungal decay.

Samples of each treatment were also evaluated in a sandwich test. Briefly, a total of 30 samples, 275 mm long, were cut from the boards in each treatment. Three pieces from a given treatment were combined and tied together with plastic zip-ties.

The assemblies were then exposed on aluminum racks approximately 450 mm off the ground. These assemblies are designed to trap water between the individual layers and encourage fungal colonization on the board faces.

Test assemblies in this procedure sometimes use a non-treated sample in the middle to serve as a decay susceptible feeder for decay fungi to grow before they attack the treated test pieces on the outside. However, this seemed to be unfair for the barrier systems, given the thin coating they present on the surface. Instead, all three pieces were composed of the same treatment.

These assemblies were visually assessed for degree of decay by removing the zip-ties and assessing the surface condition of each piece on a scale from 10 (no decay) to 0 (complete failure). Decayed or suspicious areas were further probed with a sharped tool to determine the extent of any damage. The sandwiches were reassembled and placed back on the racks for additional exposure. A total of 10 sandwiches were exposed per treatment.

3. Results and Discussion

Ground Proximity Termite Tests

Termites had completely destroyed all of the feeder material placed around the test specimens after 7, 12 and 18 months of exposure (Table 2). This indicated that conditions were suitable for aggressive termite attack over the entire test period. The covers had kept the specimens dry, meaning the exposure approximated a UC2 or UC3A exposure.

Table 2. Condition of blocks treated with various preservative systems and exposed to Formosan termite attack for 18 months in Hilo, Hawaii using an AWPA E26 Ground Proximity termite test.[a]

Treatment	7 Months		12 Months		18 Months	
	Average Rating	*Samples Remaining*	*Average Rating*	*Samples Remaining*	*Average Rating*	*Samples Remaining*
Untreated	5.53 (2.80)	13	1.3 (3.3)	2	3.1 (3.3)[b]	8
Eco Red Shield I	0.27 (1.03)	1	0	0	0	0
BluWood	4.00 (3.20)	10	0.6 (2.3)	1	1.8 (2.4)[c]	6
Timbersil	8.40 (2.02)	15	8.0 (3.3)	15	9.0 (1.1)	15
Copper Azole	9.77 (0.37)	15	9.9 (0.3)	15	9.7 (0.8)	15

[a]Values represent means of 15 specimens per treatment. Figures in parentheses represent one standard deviation.
[b]New untreated control samples were installed at 12 months to confirm that termite attack was continuing.
[c]Additional BluWood samples that were damaged were installed at 12 months.

Ground Proximity Decay Tests

Samples exposed in the Ground Proximity test were heavily colonized by dark pigmented fungi and algae on the upper wood surface, but have not yet begun to show substantial fungal attack. Untreated Douglas-fir heartwood controls had average ratings of 9.6 with only spots of decay on the edges of the samples after 30 months of exposure (Table 3, Figure 2-4). Douglas-fir heartwood is moderately resistance to fungal attack. The effect of larger specimens on decay rates Is unclear. While there is more wood to decay, a larger specimen also results in a more stable moisture environment away from the surface and this could encourage more rapid decay. In this exposure, however, wetting is nearly continuous, negating the value of the larger specimens. The degree of decay observed is typical for a ground proximity test at this location and we would expect more substantive attack in the coming year.

The Eco Red Shield I, BluWood, and Timbersil samples have begun to experience decay on the lower surfaces (Figures 3) and had ratings that were slightly lower than those for the non-treated controls, although the degree of decay remains small. These results suggest that the performance of the alternative treatments is not markedly different from the non-treated control. The copper azole treated samples were all free of visible decay (Figure 4).

Figure 1. Example of a termite array with samples treated with Eco Red Shield II, HiBor or left untreated in the E26 Ground Proximity termite test after installation in June 2015.

One continuing observation has been the extreme weight of the Timbersil treated samples. These blocks were extremely hygroscopic. It is unclear how this water retention will affect performance, but we have also noted wood fibers pulling from the upper surfaces in a pattern that resembles salt damage on wood exposed in marine environments. While the depth of damage is slight, it would certainly mar wood appearance in a decking application.

Table 3. Condition of various wood samples exposed to fungal attack in an AWPA E18 Ground Proximity test for 30 months in Hilo, Hawaii.

Treatment	*Average Condition*[a]		
	18 months	*24 months*	*30 months*
Control	9.90 (0.20)	9.84 (0.32)	9.62 (0.6)
Eco Red Shield I	9.86 (0.20)	9.61 (0.58)	9.54 (0.4)
BluWood	9.90 (0.20)	9.77 (0.35)	9.5- (0.9)
Timbersil	9.90 (0.20)	9.53 (0.76)	9.42 (0.4)
Copper Azole	9.98 (0.08)	10.00 (0)	10.00 (0)

[a]Samples were visually assessed on a scale from 10 (no damage) to 0 (complete failure). Values represent means of 35 samples, while figures in parentheses represent one standard deviation.

Figure 2. Example of an E18 Ground proximity decay test prior to the 18-month assessment after removal of vegetation showing heavy algal growth on the upper surfaces.

Figure 3. Examples of a non-treated control (left) showing extensive surface growth and slight decay and an Eco Red Shield I sample showing white fungal growth and decay.

Figure 4. Example of a BluWood ground proximity sample after 24 months of exposure showing decay pockets with concentrations of the original blue dye used to color the wood.

Figure 5. Example of a Timbersil treated sample from a sandwich test showing the collection of wood fibers on the upper, UV exposed surface.

Above Ground Sandwich Tests

As with the Ground Proximity decay tests, the sandwich samples were UV degraded on the upper surfaces, but there was no evidence of fungal attack on any of the samples after 7 or 12 months.

The sandwiches were disassembled after 18, 24, and 30 months of exposure (Table 4). Untreated Douglas-fir samples had average ratings of 9.9 after 18 months, as did the BluWood and Timbersil treated samples. As with the Ground Proximity decay tests, the Timbersil samples were water-logged and fibers were flaking off the upper, ultraviolet light exposed surfaces. The copper azole-treated samples had no evidence of decay and had an average rating of 10 (Figure 5).

The Eco Red Shield I treated samples had a slightly lower rating than either the controls or the other treated samples at 18 months; however, virtually every middle sample in the sandwiches treated with this system had evidence of fungal mycelium and decay (Figure 6). While this attack had not yet progressed to an advanced stage, the samples had pockets of bleaching and fungal mycelium on the surfaces between the sandwich pieces. These results suggest the Eco Red Shield I material has begun to experience active fungal attack. One BluWood sample also exhibited evidence of decay on the middle board of the sandwich (Figure 7).

Figure 6. Example of the center sample of an Eco Red Shield I treated sample after 18 months of exposure in the sandwich test showing surface decay.

The trends noted at 18 months continued to progress after 24 and 30 months. The copper azole treated sandwiches remained free of visible damage, but decay had become evident on many of the other sandwiches.

Decay continued to progress on the Eco Red Shield I sandwiches and all of them had some visible decay. One sandwich treated with this system had an element that was close to failure (Figure 8). Minor decay was also noted on two of the non-treated controls, but the remaining controls were sound.

Decay pockets were also noted on one BluWood sandwich, but the remainder were sound. Timbersil samples continued to be extremely heavy due to water absorption and fibers were again evident on the upper surfaces. The fibers noted at the 18-month inspection had been removed, so these were new fibers exfoliating from the surface.

The sandwich tests indicate the Eco Red Shield I samples are decaying much more rapidly than the other treatments.

Figure 7. Example of the middle sample of a BluWood sandwich showing white fungal mycelium and slight surface decay after 18 months of exposure.

The samples exposed in June 2015 were not opened since this test requires some time for decay to develop. These samples will be observed in December 2016 (18 months), but only opened and inspected if there is obvious evidence of decay.

Table 4. Condition of various wood samples exposed for 30 months as sandwiches in an above ground test in Hilo, HI

Treatment	*Average Condition*[a]		
	18 Months	*24 Months*	*30 months*
Control	9.90 (0.23)	9.75 (0.42)	9.4 (1.3)
Eco Red Shield I	9.47 (0.27)	9.02 (0.72)	8.90 (1.0)
BluWood	9.90 (0.18)	9.89 (0.27)	9.90 (0.2)
Timbersil	9.90 (0.18)	9.83 (0.33)	9.40 (0.6)
Copper Azole	10.00 (0)	10.00 (0)	10.00 (0)

[a]Samples were visually assessed on a scale from 10 (no damage) to 0 (complete failure). Values represent means of 10 samples, while figures in parentheses represent one standard deviation.

Figure 8. Example of an EcoRed Shield I sandwich showing advanced decay on the outside of the sandwich.

4. Conclusions

Termite attack of EcoRed Shield I and Bluwood treated materials was similar to or greater than that found with non-treated Douglas-fir. The former samples were heavily damaged after 6 months of exposure and destroyed by 12 months. TimberSil treated material experienced some termite attack but remained serviceable after 18 months. Copper azole treated material experienced slight termite grazing but no substantial attack. Decay is becoming visible in the Ground Proximity test, with all but the copper azole treated experiencing decay after 30 months of exposure. Decay is continuing to progress in the sandwiches, with Eco Red Shield I once again experiencing the most damage after 30 months of exposure. The results indicate that topical surface treatments perform poorly against both Formosan termites and decay fungi in non-soil contact under conditions conforming to UC3B exposures. The silicate system performed better than the surface treatments but did experience more termite attack than the copper azole treated wood. The results illustrate the benefits of proper treatment for wood exposed in UC3B applications and the need to perform comparative field evaluations of new materials.

5. Acknowledgements

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MOULDICIDES

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1. Introduction

There are a number of situations requiring mould growth to be controlled or remediated, including its growth on forest products during manufacture, storage, and transport, and on wood in service. Mould growth affects marketability of wood products andmould has been implicated in sick building syndrome as one of several elements that are part of damp dwellings where human health may be compromised (Institute of Medicine of the National Academies, 2004) . Updated and detailed definition and key biological traits of mould and how it differs from bluestain, decay, or fungi causing black stain in service were given in Uzunovic, 2016. In summary, mould is an artificial category of fungi that look like smudges of fuzzy growth caused by micro fungi from different fungal phyla on various substrates including wood products. In the majority of cases the growth is superficial on wood but sometimes some mould fungi may penetrate deeper in the wood. Mould structures, that are often pigmented in a range of colours, discolor wood by growing on it as pigmented mycelium of sporing structures and spores or through diffusion of pigments they may produce. A number of mould genera are also part of other fungal categories including plant pathogens, human pathogens, food contaminants, spoilage organisms, and biological control agents, part of sapstain causing building envelope fungi (sick building syndrome). Mould fungi pose a challenge to control because there is a large variety of genera and species with various capabilities. Many moulds are cosmopolitan and widely spread and are present in the air in the form of dry, easy-air-carried spores or propagules. Often moulds possess amazing survival capabilities, may produce complex chemistries while exploring or maintaining their food source at different substrates, and may show high tolerance to unhospitable substrates (e.g. chemically treated wood, dry wood).

Specifically in regard to wood products, mould growth can occur almost anywhere in the wood processing chain starting from standing trees where mould growth could occur on bark or branches and leaves, buds, twigs, or on wounded tissue with exposed phloem, cambium, and wood xylem. There will be a succession of different mould fungi in association with ageing of the wounds. Succession of mould growth often occur on logs during storage and transport in association with varying levels of bark damage, nutrient, moisture, and chemical changes on the exposed surface due to the drying process, aging, host response mechanisms, and colonisation by other competitive microflora. When wood is processed into lumber mould growth can occur during green storage, after heat treatment, after chemical treatment, or following drying and subsequent rewetting due to rain or condensation. Mould is also found on composite wood products such as veneers, plywood, oriented strand boards, and other engineered wood products where moisture or high humidity support the mould growth. Mould growth can also occur during transport and distributor and site storage site of wood products, during construction, and on wood is in service under many different scenarios where elevated moisture and high humidity are among the key factors to support its establishment and growth.

It is clear that there is a significant amount of scenarios in which mould growth can occur on a variety of products with different level of nutrients and presence of other chemicals (natural or applied), with a variety of moisture sources and frequency of moisture occurrence, different moisture gaining, retaining, and drying properties of materials subjected to a variety of micro climates and environmental conditions indoors, and in outdoor exposures. Under this complex scenario there is a variety of mould species that can explore these substrates and this complexity presents a challenge when developing mould control strategies that are simple, yet efficacious and with consistent performance in the context of available actives that can be used in moldicides.

2. Mould control in logs and lumber and other wood products

The key strategy when controlling mould in logs and lumber is to control moisture (make it dry and keep it dry) and would need wood drying to reduce moisture below 25% (odw). However mould growth can still occur even on dried wood under exceptionally high humidity levels (e.g. above 85%). Logs are always stored, moved, and traded green while lumber remains green for different time periods before it is heat treated or kiln dried or both. Since mould growth on logs is superficial, associated with log ends and bark wounds, it often does not represent an issue since during debarking and log squaring it is usually removed so mould control on logs is not needed. An exception is that some mould/stain preventative chemicals may be used on logs in a controlled mill situation especially for debarked logs destined for the log-home industry. The industry is likely to use similar chemicals as used for green lumber sapstain control. Log home treatments need to comply with the Pest Management Regulatory Agency (PMRA) regulations and registered products applied according to the approved label. Protection is most efficient if applied immediately after debarking. Newly-treated logs should be protected from rain to prevent leaching of chemical into the environment (Uzunovic et al., 2008).

Control of mould growth on lumber and other wood products is important and is widely practiced. Control by reducing moisture content includes storing products in open, airy places, air drying the products by stickering (stripping) or by kiln drying and preventing re-wetting, as well as reducing exposure to high humidity. Failure to control moisture efficiently and fast may lead to development of mould that can occur even within a week at optimal temperature and moisture content.

Where efficient moisture control is not possible chemical protection is needed. It is advised to follow known best practices and choose chemicals and adjuvants properly. Different companies study and develop their own practices and formulations while at the same time try to cut costs by simplifying practices or avoiding treatments in what is deemed as less problematic time periods and by reducing cost of chemicals (types, volumes, and concentrations) and that sometimes may fall beyond the threshold needed for successful control.

Treatments are typically applied in mills either by dipping or spraying or, rarely, brushing. Current best practices include a combination of narrower spectrum chemicals (since more potent and wide spectrum chemicals of the past are no longer available and are not registered for the use), with adjuvants where appropriate, in mixtures that optimize the cost/efficacy benefit ratio from the chemicals.

Minimizing the time between felling or manufacture and treatment is crucial. Chemicals need to be applied through a well-designed system that is set up and well maintained to apply a uniform treatment at target applications. Treaters must ensure that treatment liquids are fresh and there is no build-up of contaminants such as iron-stain precursors. There must exist a quality control program that periodically verifies that lumber target chemical retention rates are being met. Treated lumber needs to be protected from the weather or water splashes (e.g. while in transport on barges) to minimise dilution and impact of leached chemicals on the environment. Fungal presence in the wood prior to treatment (pre-infection) needs to be minimized and where it exists the retentions may need to be adjusted accordingly.

Older, broad spectrum antisapstain chemicals including organo-mercurials and chlorophenates, because of their toxicity and better penetration below the surface, were capable of dealing with established infection compared to currently available narrow spectrum chemicals. Preinfected lumber presents a significant challenge in mould control. More recent lab experiments found that several actives applied prior to exposure to seven mould fungi were most effective against spores, less so against approaching mycelium, and least effective against live mycelia already present in wood prior to treatment (Uzunovic et al., 2013a). In addition, in the same paper different actives were not performing equally against spore germination and mycelium. For example isothiazolones, IPBC, and propiconazole were less effective against mycelial growth than against spores and ineffective against well established mycelium. IPBC was most effective of the three against mycelia. Higher concentrations of different actives need to be tested to find inhibitory levels against more tolerant species used in the test, such as *Fusarium* sp.

Failure to control mould could be due to preinfection, wood being treated with suboptimal chemical retentions, unequal coverage, lower level of active substances, inappropriate mix of actives for particular challenge mould, dilution of actives due to heavy rain and outside exposure, or other factors.

Mould control needs to be applied to other wood products during production, storage, transport, and construction. Proper moisture control is the best approach and drying process (air drying or kiln drying) relevant to a particular product can be utilized and encouraged as well as kiln drying, and later ensuring that the product is kept dry and not stored under high humidity. Chemical use may be needed for specific situations where the cost is justified and similar approaches and challenges need to be addressed, as for mould control on lumber.

3. Mould control in buildings

Some wood products may develop mould growth during construction and this growth will need to be removed or products may need to be replaced before the building envelope is closed. Once the products are free of mould and in service they may support mould growth only if the moisture is present. Moisture sources vary and may be rare and sporadic, or frequently occurring or constant. The source of moisture may be through high humidity and condensation, building envelope and plumbing leaks and water ingress, floods etc. Depending on the physical property of the product and its moisture gaining, retaining, and drying properties, moisture content will vary in association with micro climates and environmental conditions. In general the more moisture and more frequent moisture events will create more mould growth.

The key approach in controlling mould is through moisture control, remediation, and prevention of recurrent moisture events. Maintenance of ambient RH to be less than 80% is recommended to prevent mould growth and condensation. Proper building design and maintenance may prevent or reduce the effect of moisture ingress and subsequent mould growth. If mould growth occurs there are a number of existing guidelines or professional companies available to address cleaning of existing mould and mould remediation. Depending on the severity of growth, different approaches are taken which often involve HEPA filter vacuuming, cleaning by scrubbing with soapy water, or removal and replacement of mouldy materials. There is still not much information and scientific experimental data available on chemical formulations to be used for cleaning, encapsulating, killing, or masking mould in situ. Some materials can easily be cleaned while some may need to be replaced. Some materials will not support mould growth and that may influence architectural design choices.

Where moisture events are predicted and unavoidable, chemical protection or use of chemically treated wood products may be needed. However there is not much information available on the type of mould treatments, retention rates, and predicted service life under different moisture scenarios and materials used, especially in the context of the safety for inhabitants of the chemicals used. Our case study presented later in the text points out some challenges and offers some preliminary solutions that are subject to a test of time in a real life situation.

4. Chemistries used in mould control and test to screen moldicide efficacy

The antimicrobial products currently used for treatments generally have a narrower spectrum activity, shorter protection time, and an improved environmental performance compared to some of the broader spectrum chemicals that were used in past such as chlorophenates (Byrne, 1998a, 1998b). From the 1990s the most common active ingredients used are azaconazole, sodium borates, Cu-8, DDAC, IPBC, and sodium carbonate. The industry realized that mixtures of two or more actives are often needed for successful control, and formulations like NP1 (mixture of DDAC and IPBC), F2 (DDAC and borax), and QC3 (DDAC and polymer) have been successfully used in Canada. However even these did not have consistent performance on all wood species and for longer periods. They have also been shown to be less effective against moulds than against bluestain fungi.

Based on a review by Schauwecker and Morrell (2008), commonly used actives included propiconazole, didecyldimethylammonium chloride, 3-iodo-2-propynyl butyl carbamate (IPBC), and diiodomethyl p-tolyl sulfone. They are mixed in different formulations with various non-active compounds to improve efficacy and cost effectiveness. They are used to control bluestain and mould fungi and additional chemical formulation attempted to control black stain fungi. For example Stirling et al., (2011) evaluated additional combinations of compounds against several types of freshly isolated challenge black stain fungi and those included IPBC, propiconazole, tebuconazole, thiabendazole, fludioxonil, chlorothalonil, oxine copper, copper metal, and naphthoquinone. Combinations of propiconazole with IPBC and propiconazole with IPBC and thiabendazole were most effective in the test.

Because most actives are carbon-based molecules that are subject to breakdown, their duration of protection on green lumber is limited. They are meant to give a few months' protection to cover the time from manufacture to export, shipping, and receipt of the wood at a building site or other end use. They do not replace wood preservatives which give greater and longer resistance to fungal attack, especially to decay (Schauwecker and Morrell, 2008).

In summary the actives currently available are greatly restricted by health and environmental regulations. Only a few new actives are likely to come to market given the high cost of developing, testing, and obtaining regulatory approvals for new biocides (Stirling and Temiz, 2014). Based on this most recent review paper, Table 1 summarizes currently used actives and chemical classes. Not all actives are allowed to be used in all countries and for example those marked with * are the ones that can be used in Canada (registered by PMRA)

Table 1. List of actives/chemicals

<u>Organic Actives:</u>

Azoles (Triazoles)
- Propiconazole*
- Tebuconazole*
- Thiabendoazole

Carbamate
- Carbendazim*
- IPBC (3-iodo-2-propynbutil carmabate)*

Chlorothalonil (Aromatics)

DDAC (quatenary ammonium compound)*

Diuron

Fludioxonil

Isothiazolone*
- OIT (2-n octyl-4-isothiazolin-3-one

CMIT (5-chloro-2-methyl-4-isothiazolin-3-one)
MIT (2-methl-4-isothiazolin-3-one)
Methylene (bis) thiocyanate
TCMTB (Benzothiazoles)*

<u>Inorganic Actives:</u>
Copper
Copper metal
Oxine copper
Arsenic
Boron
DOT (disodium octaborate tetrahydrate)*
Zinc borate
Tin based ((bis(tributyltin) oxide (TBTO))
Silver
Zinc

In addition to registered actives there are other compounds that are often not regulated and can be added to formulations that sometimes may enhance their performance. These may include various water repellent compounds or adjuvants (such as e.g. amine oxide…, Trisodium phosphate (T.S.P) etc.

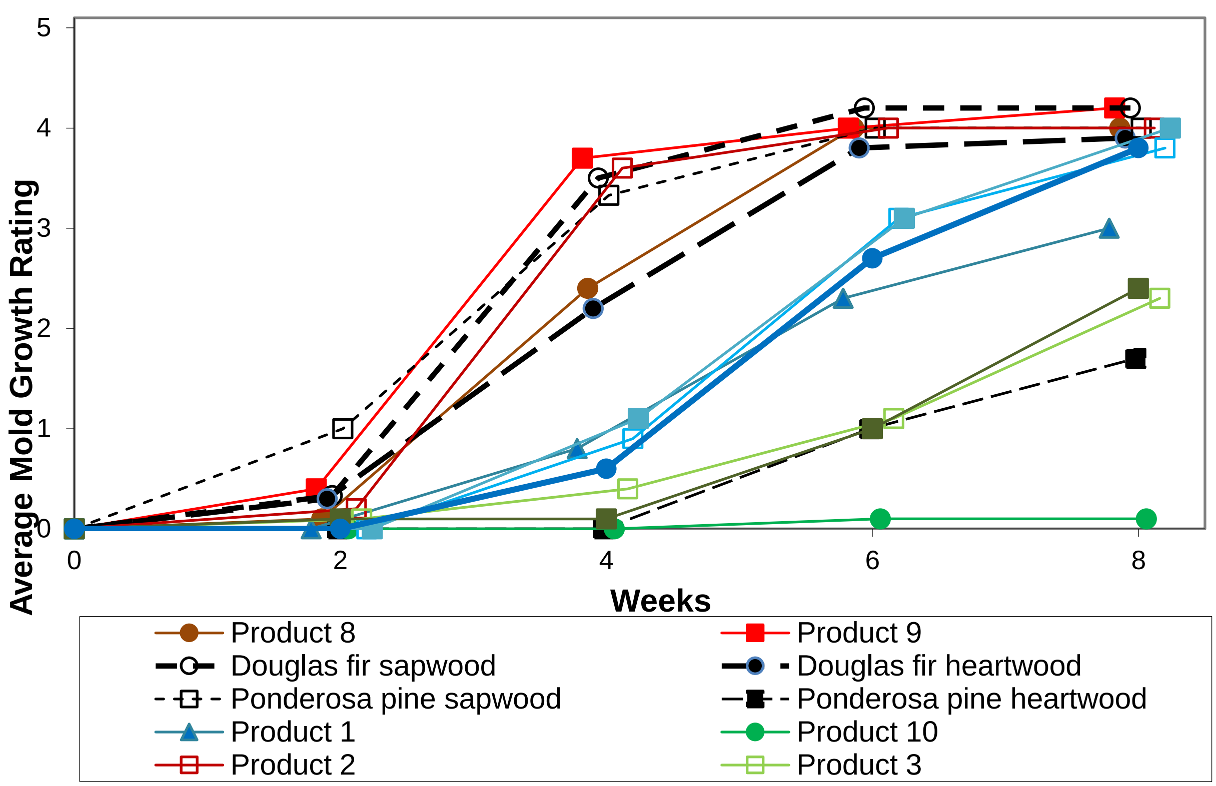
FPInnovations (former Forintek Canada Corp.) and other laboratories have extensively tested sapstain control products to protect green lumber. Various test methods have been used, ranging from laboratory to field to shipping trials and different methods produced different results so it is very important to include test methods that are representative of situations to which lumber or other wood products may be exposed in real life. Most commercially developed products for green lumber were designed to prevent bluestain rather than mould and a number of formulations have traditionally been less effective against moulds. New formulations intended to better control moulds are being constantly evaluated, and some show promise.

Some evaluation tests are lab based, done in small well plates or Petri dishes on nutrient agar or using small, sterilized wood substrates. Some tests are scaled up using sterile or not sterile wood of different size while some tests are done on a large scale in growth chambers or tent-like set ups or tested in the field under natural conditions. Some standardised tests are the AWPA E24 standard lab method for evaluating the resistance of wood products surfaces to mould growth or AWPA E29-13 antisapstain field test method for green lumber. Concerns have been expressed on how accurately lab and scaled up field test represent real-world mould growth and control.

Byrne and Minchin (2007) for example questioned how accurately the AWPA E24 method represents real-world mould growth on full dimension lumber and they developed in-house two experimental accelerated test methods, all optimal to mould growth, to compare to AWPA E24. These included a tent and the conditioning room test. Two of the three test methods provided similar results (AWPA E24 and tent) while the conditioning room test was not viable due to lack of mould growth on untreated unstained and stained sapwood. All products tested reduced susceptibility to mould growth for at least two weeks in the AWPA E24 test. In one of the viable tests, mould growth was more extensive on unstained sapwood than on stained sapwood. Both tests indicated that the products tested at the time Busan 1030, MC81-MZ95, Mycostat 3 and MC81-023 performed well.

An example of results from using AWPA E24 that evaluated ten different formulations against mould is shown in Figure 1. Some products had as good a performance or better after eight weeks as ponderosa pine heartwood (positive control) while others failed after four weeks. The results for those performing well usually give confidence to evaluate them further and use them in scaled up tests.

Figure 1. Evaluation of efficacy of ten formulations against mould using AWPA E24 test



However, the AWPA E24 uses high humidity conditions compared to the FPInnovations recently developed in house Modified AWPA E24 test method (described in the case study below), where moisture is forced intentionally to condense on the surface of test samples to mimic some situations found in real life (e.g. roof attics). Although these tests are in essence similar, the mould ratings and results are different for both treated and untreated test materials (controls) as were moisture and wetting events of different test materials. Normally ponderosa heartwood does not go above a rating of 1 in the AWPA E24 test and is used as a negative control while ponderosa pine sapwood is used as a positive control and is rated 4 and above within four weeks. However both substrates developed mould and got rating around 3 in the Modified AWPA E24 test, thus precluding them to be used as controls in the Modified AWPA E24 test. In the later test sapwood-rich Douglas-fir plywood samples were chosen as a negative control.

Our experience have shown clearly that different test methods can lead to different results, so in the development of successful moldicides it is important to select test methods that closely represent the intended use environment in order to find and verify treatments that will stand a chance against challenges in real life situations.

5. A case study of controlling mould in attics in coastal climate

As an example of the complexity of research in finding solutions for mould growth we share a summary of our recent work that looked for a solution for mould occurring on sheathing attics in coastal climates. Water vapour condensation and subsequent growth of moulds has been increasingly noticed on sheathing in ventilated attics in the Lower Mainland of British Columbia. It appeared that the roof design according to building codes cannot prevent wetting from condensation brought in by ventilation of wet humid air. It is recognised that the solution may lay in fungicidal protection. Furthermore, attics with existing mould problems needed a remedial treatment.

The Homeowner Protection Office approached FPInnovations to assist in evaluating protective treatments to prevent mould growth as well as in exploring remedial treatments for mouldy sheathing.

This work was done in four phases over three years and was funded by HPO. Phase 1 included a screening process for the most promising chemistries that are either registered or close to be registered with PMRA using AWPA E24 (ten products as represented in Figure 1) Uzunovic et al. 2013. Recognising a need for additional testing that would better mimic situations in attics Phase 2 looked into development of a new test method that become the Modified AWPA E24 to allow intermittent condensation on test samples. After the Modified AWPA E24 test was developed and verified, in Phase 3 we tested the most promising chemistries from Phase 1 using the Modified AWPA E24 (three products and four off-the-shelf water repellent products and combinations of these). Finally in phase 4 we assessed remedial treatments and masking ability of formulations by testing the best performing formulations in phase 3 and adding additional off-the-shelf products that an advisory committee of knowledgeable experts recommended at the time, using the Modified AWPA E24 method.

The Modified AWPA E24 test includes, instead of a pitched roof, one flat roof made of 2.5 cm XPS insulation, on an 20 cm extension that fits on the same base used in AWPA E24 test. The

XPS has 15 cut out holes to hold samples to 0.5 cm depth. The system includes 7.5 cm of water on the bottom; tray with unsterile soil above it, 3 days of wetting cycle (chamber at 25ºC, storage room at 18ºC, 30 minute mini-cycles of switching the fan on/off to suck cold air into the chamber) followed by fours days of drying cycle (chamber heating and fans switched off allowing natural aeration,while aiming to maintain at least 80% RH and 16 % emc).

In these tests a highly mould-susceptible substrate, sapwood surfaces of Douglas-fir plywood, was used for the test and reference materials. The products selected for testing were either registered by Health Canada's Pest Management Regulatory Agency, or in the process of applying for this registration, and were applied according to the label.

It was found that because of how different substrates take in extra water and how long they hold it under different drying regimes different control substrate including solid woods heartwood and sapwood, plywood and OSB behave differently in the experiment, showing different beading, cupping, moisture distribution and drying. This clearly affects their susceptibility to mould as well as the performance of any mouldicides used. Table 2 contains a description of products used in Phase 4 of experimenting.

Table 2 Products tested using modified AWPA E24 test, for their ability to eradicate, encapsulate or mask existing mould

Products	Product Description
Product A	This is a non-commercial product. It was an experimental formulation incorporating multiple active ingredients at high concentrations (as a positive control) applied at 6:1 dilution of the product from the concentrations used originally in phase 1 of the project
Product B	Industrial blue-pigmented moisture and mould-resistant coating for kiln-dried lumber, used as received. Performed well in phase 1 and 3
Product C	Industrial unpigmented moisture and mould-resistant coating for kiln-dried lumber, diluted 35:1. Performed well in phase 1 and 3
Product D	Retail white water-based interior/exterior primer, sealer and stain-blocker, used as received
Product E	Retail mould remediation and prevention treatment containing trisodium phosphate, used as received
Product F	Retail mould resistant sealer, used as received
Product G	Commercial preventive and remedial wood preservative to protect against decay, beetle attack and mould growth, used as received

Rating included the extent of mould prior to remediation, efficacy of cleaning agents in reducing discoloration and re-growth. masking ability of a treatment, new mould growth rating after treatments, and overall mould appearance

Rating of previously moulded and cleaned products was challenging and, to an extent, subjective. What appeared to be mould and mould stain for some may not be for others, as we conducted an overall appearance rating test. The previous mould staining caused an issue between raters as some included it in the overall appearance rating while others did not. The perspective of a consumer needed to be considered from the onset of this test which is represented in the overall appearance rating.

Another highly discussed property was the overall appearance of each treatment, speculating what consumers may prefer such as the clean white paint-like look of Product D while others might like the deep blue colour of the Product B product. Some consumers may still prefer natural wood colour when Product F or Product G products were used knowing that they both successfully prevented regrowth or new mould growth but show previousl mould growth.

In these tests Product D (white) had the best rating over non-cleaned samples. It combines masking ability and new growth prevention and is great for one-step remediation. B (blue) also performed well, and was superior in preventing further growth but not completely masking underlying mould.

Cleaning reduced ratings from 5 to 1. Bleach cleaning appears to be the best cleaning method and most cost effective (sprayed-no scrubbing) but non of the cleaning methods alone were not sufficient to prevent new growth. Products A, B, D, F, and G all showed the ability to prevent mould regrowth but A, F, and G did not mask existing stain.

6. Conclusions

It is challenging to control mould due to the limted amount of registered actives with narrower spectrum activity aiming for shorter protection time. The challenge include variety of mould species present with their capabilities that can tolerate hospitable environments or even able to decompose the actives, variety of substrates (chemical constituents, nutrition, moisture uptake and hold, etc.) in the context of constantly fluctuating conditions in time. These factors in combinations either enhance or slow mould growth, can affects the efficacy of chemicals used, or moisture uptakes and fluctuation in the substrate.

No single chemical can control all the complexity within moulds. Actives are limited and likely to be even more restricted in future. Effective strategies can be developed for particular situations but no single treatment can be effective in all circumstances.

Systems approach is the best strategy where combining moisture control with awareness of particular scenarios and organisms involved, nature and restrictions of chemicals (tested with carefully chosen tests) and good quality control. Additional attention could be paid on specific selection of test materials to represent commercial operations and if used in dry-service or service with occasional moisture. Also one could include in the test conditioning prior to in service use – e.g. to be subjected to leaching due to construction moisture for coastal areas and non-coastal areas (vertical or horizontal elements). Different substrates may behave differently (solid wood, plywood, OSB, CLT) so they all need to be included in the test if a chosen moldicide is expected to perform on all of them.

Tests to assess candidate formulations need to be chosen carefully to present as close to real life situation as possible and the results only give a good guidance and confidence to step into field testing to verify compounds in real life. Over time it will show how the formulations really stand.

Any successful control needs to understand this complexity, and aim for a particular well-defined scenario, tailoring the protection system while optimizing individual factors that may affect the performance in order to be successful.

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PRESERVED WOOD AQUATIC ASSESSMENT TOOL

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1. Introduction

The use of preserved wood products in aquatic environments is a common practice developed to protect the wood from degradation by organisms capable of consuming wood. Preserved wood is a concern in Endangered Species Act (ESA) and Essential Fish Habitat (EFH) consultations because wood preservatives do leach or migrate from pressure treated wood at known rates. The rate of leaching drops off rapidly following installation, but research has indicated that there is a potential for sub-lethal effects on listed species[1].

More than six decades of research on preserved wood products used in and above water have been compiled. "Managing Treated Wood in Aquatic Environments" written and edited by Jeffrey J. Morrell, Kenneth M. Brooks and Caryn M. Davis was used as the basis for developing an Aquatic Impact Assessment Tool. It was developed by Ken Brooks and is maintained by the Oregon State Environmental Performance of Treated Wood Research Co-op lead by Jeff Morrell.

The non-profit trade associations representing the wood preserving industry in North America paid to have this aquatic assessment tool updated from an Excel file to an online form that can be tracked, saved and utilize. These associations are the Wood Preservers Institute, Treated Wood Council, Timber Piling Council, Creosote Council, and Wood Preservation Canada.

2. Methodology

Efforts to minimize impact from the preservatives have resulted in improvements to processing such as the Best Management Practices also published by WWPI, SPTA, WPC and Southern Forest Products Association. Based on this research and the BMP's a model was developed to show what affect, if any, movement of the preservative into the aquatic environment would have.

The model looks at piling as well as decking and other durable preserved wood products that can be in and over water, in wetlands, rivers, lakes, and the ocean. The model is looking at a worst case scenario with inputs form the different state, and national benchmarks. The online form can be modified to suit any project or regulatory benchmark it needs to meet and whether or not preserved wood can be used with minimal impact to the environment.

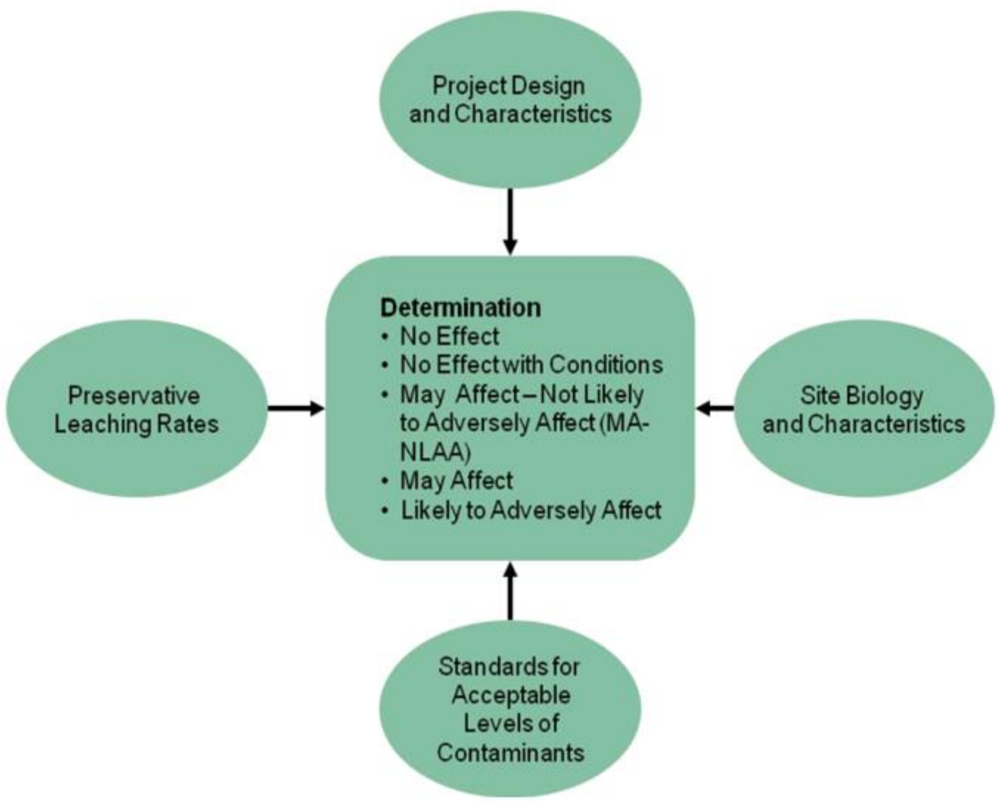
3. Results and Discussion

The peer reviewed model of leaching rates and risk potential developed to support decision making are designed to lead the user to one of five determinations regarding consultation.

These "effect" determinations will be helpful in assessing the potential impacts of the proposed project and assessing whether the project can proceed with informal or formal consultation.

1. A "no effect" determination;
2. A determination that with specific special conditions a "no effect" determination can be reached;
3. A "may affect, not likely to adversely affect" determination which may allow consultation to be completed through informal consultation;
4. A determination that with specific special conditions a "may affect, not likely to adversely affect" determination can be made which may allow consultation to be completed through informal consultation;
5. A "likely to adversely affect" determination which will require formal consultation.

Figure 1 below shows project characteristics that influence the model.



Screening Level Assessment Process April 2011, courtesy of WWPI

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4. Conclusions

Preserved wood should still remain the first and most reliable choice for piling, decking, railing and other aquatic structures. Such wood structures are able to handle hurricanes, floods, wind, and seismic activity as well as lasting the life of the project. Using the model to determine the impacts on the environment, if any are critical to moving the project forward with regulatory approval. For more information on the model please follow the links on www.preservedwood.org to the OSU EPTW Co-op website where the model is hosted.

5. Literature

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3. Risk Assessment Model is available at www.preservedwood.org

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DUAL TREATED CROSSTIES ETC.

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Summary

The heartwood of most wood species is not treatable by vacuum pressure processes and very often leads to premature failure of larger commodities, such as Douglas fir poles and white oak and hickory ties. Traditionally these issues have been managed by high cost remedial or *in situ* applications, or short service life and product replacement. Research by many workers over many decades has led to the current commercial practice of dual treatment in order to overcome these limitations. It is defined here as two disparate preservative systems, a water diffusible system and an oil-borne pressure impregnated system, being applied to the same piece of wood often as two (dual) treatments at different times. Essentially this is the same as using an oil-borne preservative, and then carrying out a remedial treatment, but has the benefits from the first day of service life, or even before that if the commodity is air dried before treatment.

Adding borates to railroad crossties prior to creosote treatment has been shown to provide significant benefit to railway crossties (Amburgey *et al*. 2003, Anon 2010) and utility poles (Dickinson and Murphy 1991). Currently, nearly 50% of the 22 million wood ties produced in the United States are dual treated with an initial diffusible borate application for heartwood protection. The multi-billion dollar potential savings possible with this approach especially in the southeast of the USA has been documented (ZetaTech 2011). It should also be noted that the inclusion of borate has allowed the industry to reduce typical creosote retention from for example a specified 8 pounds per cubic foot (pcf) or 128 $kg \cdot m^{-3}$ to a specified 6 pcf or 96 $kg \cdot m^{-3}$ so the borate treatment is more than paid for with creosote savings, let alone the improved longevity.

Treatment of bridge ties has now also been commercialized using a further modification of this approach, with even higher unit cost savings (up to $1 billion across the network assuming only a 5 year life extension. Lloyd *et al*. 2017) and commercial testing is now underway in utility poles.

1. Borates in Wood Protection

Since the 1940s, borates have been used as wood preservatives due to their broad efficacy against wood destroying organisms including those tolerant of other preservative systems, low cost, low mammalian toxicity, and low environmental impact (Cockroft and Levy 1973, Dickinson and Murphy 1989, Lloyd 1997). The chronic toxicity of borates (documented since the 1970s) is similar to that of alcohol in beer or wine, but with obviously less risk of ingestion. For details of boron essentiality and toxicity see ECETOC (1995) and Lloyd (1998).

The solubility and mobility of borates enable them to diffuse in wood and this is advantageous in treating refractory species that are difficult to treat by vacuum pressure methods. It has been demonstrated that extended immersion of green lumber in concentrated borate solution, followed by a diffusion period can produce satisfactory penetration in many wood species (Smith and Williams 1969, Cockroft and Levy 1973, Barnes *et al*. 1993, Fowlie *et al*. 1988, Puettmann and Schmidt 1997, Schoeman *et al.* 1998, Wang *et al*. 2007, Taylor and Lloyd 2009) and this was also recently shown with ambient temperature dip treatment (Kim *et al.* 2011).

Research on pressure treatment of lumber with borates has shown that penetration equal to or exceeding other types of preservatives is possible (Baker *et al*. 2001, Lebow and Morrell 1989, Lebow *et al.* 2010, Morris *et al.* 1996).

In the USA stand-alone borates are used as disodium octaborate tetrahydrate (DOT) by traditional vacuum pressure and diffusion processes as treatments to protect sill plate, framing lumber in construction and log home logs (AWPA Standard U1, Section 6. Commodity Specification I: Nonpressure Applications) and for the protection of railway ties during seasoning, and in use, after over treatment with copper naphthenate or creosote (AWPA Standard U1, Section 6. Commodity Specification C: Crossties and Switchties). Specifications for Inorganic Boron (SBX) are listed in AWPA Standard P25.

Other than as a stand alone preservative, borates have been widely used in formulations. The first use of borates was probably in the chromium boron formulation developed by Wolman in 1913. Borates were then used to replace dichromate in flame retardants (Falck and Ketkar 1934) and promising efficacy data was develop by Bateman and Baechler (1937). They were subsequently used in the very successful diffusible formulations used in Papua New Guinea from the 1950s, CCB instead of CCA in Germany, ACQ and CA, ACZA plus B in the USA (Lloyd 1993 and 2013). As yet, no wood decaying fungi has ever been reported to be tolerant to borates at normal preservative retention (Dickinson and Murphy 1989). This attribute combined with the diffusion and penetration capabilities make borate an essential component of many effective preservative formulations.

They have been widely used in copper based formulations such as the original ACQ type D (amine copper quaternary ammonium compound with boric acid) and in the CBA formulations (copper boron azole) although recently due to commercial and competitive pressure, the borates have often been removed from such formulations, which may have been one of the causes of the many anecdotal premature failures of such water borne copper systems, especially in decking (it is proposed that this may be a penetration and detoxification issue combined with the variability in treatment with products applied close to their toxic thresholds, all of which the borates could help alleviate or previously prevented. Lloyd *et al*. 2013).

ACQ and CA-C have been seen to have decay issues within 5 years of service due to preservative penetration and detoxification issues (Chrome Azurol-S reagent shows remining active copper as blue).

Borates have also been used successfully in a remedial capacity, especially in the treatment of operational (in service) creosoted poles and railway ties (Richardson 1978, Dicker *et al.* 1983, Dickinson *et al.* 1988, Hennington *et al.* 1989, Dickinson and Murphy 1989).

Untreated heartwood of a Douglas fir utility pole showing internal decay cavity.

Incipient decay in air seasoned poles shown by many (Panek 1963, Mills *et al.* 1965, Zabel *et al.* 1980, Graham and Corden 1982, Wilcox 1984, Morrell *et al.* 1987, Roff 1984, Dickinson and Murphy 1991, Wikander 1982, Mills *et al.* 1965, Taylor 1985) has also been successfully prevented using borates (Dickinson and Murphy 1991, Lloyd 1993 and 1994) and it was possibley the combination of the successes in remediation and control of incipient decay that led to the work on tie dual treatment.

2. Borates in Ties

Over 95% of railroad cross ties installed in the USA are made of wood treated with preservatives such as creosote or copper naphthenate. Wood is more cost effective and is much more environmentally friendly than alternatives such as concrete, steel and composites, as shown in life cycle assessment for ties and poles (Townsend and Wagner 2002, Smith and McIntyre 2011, Bolin and Smith 2013). The wood is preservative treated to protect against decay fungi but also termites and other wood destroying organisms, and thus to ensure adequate service life.

However, long air-drying periods are required before treatment with oil-borne preservatives. During this time, incipient decay, known as 'stack burn,' can develop. Incipient decay can reduce wood strength, can serve as inoculum going into service and can cause poor final creosote treatments due to localized pockets of high moisture content (Taylor 1985). Moreover, some wood species, especially white oaks and hickory, are not completely protected, due to poor creosote penetration in these refractory species (Amburgey *et al*. 2003, Dickinson *et al*. 1990).

Creosote does not penetrate the heartwood and so only the envelope of ties is protected from decay as can be seen in the sectioned crosstie taken out of service.

Borates were first used to dual treat ties in the 1960s in Malaysia due primarily to the high cost of creosote. In one study, leaching was observed over a five-year period and, whilst borate retention dropped significantly, it remained above the toxic threshold (Arthur 1967). In large dimension treated wood it typically takes a very long time for borate retentions to drop below decay fungi toxic thresholds (~ 0.1% DOT, or 0.76 kg·m^{-3}) (Lloyd 1995 and 1997).

***Neolentinus lepideus,* "The Train Wrecker" growing on a creosote treated bridge timber.**

Treating railroad crossties with borates prior to creosote has since been shown to prevent decay during drying and in-service (Amburgey *et al*. 2003). Today, dual treatments are being specified to both increase tie performance and reduce creosote usage (by approximately a third). Borate treatment of ties can also control creosote detoxifying and resistant fungi (such as *Cladosporium resinae* and *Neolentinus lepideus*), protect against corrosion induced decay around spikes and screws ('spike kill') (Amburgey *et al*. 2003; Amburgey and Sanders 2009), and reduce the potential for the tie to harbor subterranean termites after retirement.

Taylor and Lloyd (2009) previously demonstrated the ability to treat ties using a hot dip diffusion treatment and found an extended dip in 10 and 20% DOT solution at 65, 80 and 93°C could achieve borate retention requirements and meet phytosanitation standards.

Rail spikes place in a beaker of 1 % DOT (left) and water (right) show the anti corrosion benefits of sodium borates (48 hours).

Whilst it has been estimated that decay accounts for only 18 to 35% of tie failures (Bescher 1977), decay fungi have a significant influence on many important wood properties and, likely, when deterioration is not readily visible in early stages of decay, mechanical tie failures are influenced by strength losses caused by decay fungi. Thus, many losses attributed to crushing, plate cut, spike kill or splits may in fact be due largely to decay. Treatment procedures that result in the penetration of preservatives throughout most or all of the cross-sections would significantly decrease or prevent these premature failures.

The work of Amburgey, *et al*.(2003) ultimately culminated in a field trip organized by the Railway Tie Association to Cordele GA and the 23-year-old test site there (Anon 2010). Side-by-side comparisons of white oak treated with just creosote failing with their centers rotted out and already having been replaced once, or with Creosote and DOT in 'near perfect condition' were arguably the single most important event that has now led to the widespread commercial use of such dual treatments by class one railroads in the USA.

Dip treatment in high concentration DOT solution has a major advantage over pressure treatment method as it treats all species equally or to approximately the same retentions. This is especially beneficial because it is difficult to achieve required DOT retention in some refractory species such as oak and hickory especially when they are treated simultaneously with other species. Secondly, pressure treatment with a low concentration DOT solution can increase moisture content of the dried ties, which would adversely affect the subsequent creosote or copper naphthenate treatment.

Not all tie processors have the capability to borate treat green ties, but the benefits in service are still probably sufficiently good enough to warrant adding borate to ties even after air seasoning. This is done using a light empty cell treatment of hot DOT solution at about 18% followed by immediate pressure treatment with creosote, typically in the same cylinder. This process is often called the 'one and a half step' treatment to differentiate it from the two step process. The various methods, their potential advantages and treatment requirements have been described (Taylor *et al*. 2013).

New two-step tie sections cut and curcumin sprayed (borate shows as red/orange after Smith and Williams 1969) courtesy of Dr. Nate Irby Union Pacific. Borate penetration can be seen to be much greater than the creosote penetration, even at this early stage of tie life.

Because of the low surface-area to volume ratio and the large (refractory) heartwood percentage of bridge ties, pressure treatments with dissolved borate are unlikely to result in sufficient treatment penetration and retentions, especially in green timbers. The high-concentration borate emulsion dip treatment being used successfully for railway crossties (Kim *et al*. 2011), works by allowing the borate to diffuse into the wood after the initial dip treatment (on the un-dried tie) for a number of months during drying, before over-treating with the second preservative. Bridge ties can be different sizes for every bridge, are difficult to stock and so are typically ordered 'just in time' per project. For this reason they are usually dried using a Boulton process: boiling out the water by submerging the green timber in heated preservative under vacuum, so do not have the many months of drying time to facilitate dip or pressure diffusion approaches.

In the South East USA, creosote only bridge tie average life is about 16 years. Here the heartwood of this gum bridge tie is completely gone.

These problems have been successfully overcome by drilling holes in the timber and filling them with 50% liquid borate preservative. The preservative is then mobilized during the Boulton treatment and results in a very well treated heartwood (Lloyd *et al*. 2014). Potential concerns of strength loss or possible reduction in mechanical properties caused by the drilling of the holes has been addressed (Bennett *et al*. 2016). This approach has been added to the Norfolk Southern Bridge Tie Specification and commercialized by both Mellott Wood Preserving and Stella Jones Corporation.

Commercially dual treated borate (Cellutreat® liquid 50) and copper naphthenate (QNAP®8) bridge timbers. Timbers have been rip sawn after borate and plug BTX®) installation and Boulton treatment, and one half subsequently curcumin sprayed (Smith and Williams 1969) to show the presence of borate (red).

3. Conclusion

If the work with crossties and then bridge ties was a logical step from the remedial treatment and pretreatment protection successes with borates in poles, it is only right that the opportunity with poles is now being looked at again following the huge commercial success with crossties. Wood is the best material by far, and ties, bridges and poles made from a renewable natural resource, dual treated with non-restricted use preservatives (borate and copper naphthenate) to maximize their service life and save billions of dollars, can only help maintain wood as the material of choice.

Douglas fir utility pole rip sawn and curcumin sprayed for boron immediately after treatment (shown as red after Smith and Williams 1969). The diagonal holes were filled with an aqueous borate concentrate (Cellutreat® liquid 50) and the pole was then Boulton treated in Copper Naphthenate (QNAP®8).

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ENHANCING THE EFFICACY OF CARBON-BASED PRESERVATIVES IN GROUND CONTACT

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Summary

A wider use of carbon-based preservatives (CBP) is limited by their poor performance in ground-contact applications. Carbon-based preservative formulations were modified to improve ground-contact decay resistance and placed in soil-bed decay tests intended to promote basidiomycete or soft-rot attack. After 17 months of incubation, significant decay was observed in all treatment groups, with the exception of the ACQ-treated reference. It was concluded that in order to improve the performance of carbon-based preservatives in ground contact, the microorganisms that are tolerant to them, or that detoxify them, need to be identified. A second study used DNA sequence based microbial community analysis methods to identify the organisms present during the degradation process. After 32 weeks of exposure carbon-based preservative-treated wood was slightly decayed. At this time there was no evidence of azole degradation; however, between 23 and 66% of DDAC had been lost from carbon-based preservative-treated samples. Twelve bacterial operational taxonomical units (OTUs) and eleven fungal OTUs were widespread in CBP-treated samples, but not detected in the ACQ-treated reference. These organisms should be further studied and evaluated for their ability to degrade quaternary ammonium compounds, and decay wood.

1. Introduction

Modern residential wood preservatives are dominated by copper-based systems. Copper is cost competitive, highly effective, and has low human toxicity; however, there are concerns that copper leached from preserved wood could negatively affect aquatic environments (Morrell *et al*. 2011). As a result, in some jurisdictions there are some restrictions on the use of copper-based preservatives in and near aquatic and sensitive habitat. Since further restrictions are possible, it would be wise to have alternative carbon-based (metal-free) systems available.

There are a handful of commercial carbon-based preservatives used for treating residential wood products globally. Most of these products are based on combinations of quaternary ammonium compounds, triazoles, and/or isothiazolones. The development of new actives for wood preservation is prohibitively expensive, so there are only a small number of carbon-based biocides available (Stirling and Temiz 2014). All of these are effective against wood rotting basidiomycetes but biodegradable in soil. Only a few are effective against soft-rot fungi (Forster et al 2002). Consequently all of these systems are restricted to above-ground applications, which hold back the expanded use of carbon-based preservatives. Canadian treaters are not keen to use more than one wood preservative in their treating plant, and the big box stores will not stock two

SKUs of any one size of treated wood, one for above-ground and one for ground contact. Consumers prefer all treated wood used in a particular structure to be the same colour.

Preservatives need to protect against decay fungi, but also need to be resistant to detoxification by bacteria and fungi. Carbon-based biocides can be detoxified by a wide range of microorganisms. This is believed to be one of the reasons for their poor performance in ground contact. However, relatively little is known about the nature of the organisms responsible for detoxification of carbon-based preservatives systems in ground contact (Wallace and Dickinson 2006). The identity of these organisms is needed to develop more effective control strategies.

Traditional identification of the organisms associated with wood decay faces several challenges. For example, many microorganisms do not produce structures that are easily visible to the naked eye or, in the case of bacteria, can be completely undetectable by eye during most of their life cycle, especially in soil or wood. In order to identify these organisms using traditional methods, culture-based techniques are used; however, an *a priori* knowledge of their growth requirements is needed in order to isolate them. Due to these limitations, many species likely remain undetected. DNA-metabarcoding can be used to overcome some of these limitations. Rather than attempting to grow the organisms present in a community, all of the DNA present from all of the microorganisms is simultaneously extracted in a single reaction. Using next generation sequencing technology, DNA of the whole community is sequenced. By using probes to target specific groups such as fungi or bacteria and specific regions of DNA useful for identification, each DNA sequence generated can be separated and used as a barcode to identify the individuals present in a sample. DNA barcoding has successfully been used to investigate the fungal and bacterial communities associated with untreated and treated wood in ground contact (Noll and Stephan 2010; Kirker *et al.* 2012a,b), as well as above-ground (Råberg *et al.* 2007; Kirker *et al.* 2014).

The first part of this work examines the impact of selected co-biocides and adjuvants on the performance of carbon-based preservatives in ground contact. The second part of this work examines the microorganisms associated with the carbon-based preservative-treated wood during the early stages of decay.

2. Methodology

2.1 Initial Evaluation of Modified Carbon-Based Preservatives

A soil-bed decay test was initiated based on AWPA E14-07 (AWPA 2012). Ponderosa pine (*Pinus ponderosa*) sapwood stakes (12.5 x 12.5 x 508 mm) were sorted by density and allocated to different treatment groups. Stakes were treated with the preservatives listed by code in Table 1, using a typical full-cell process. They were then cut into two daughter stakes for installation into test, and an analysis biscuit. Gauge uptakes were calculated, and ten stakes from each treatment group with the most similar uptakes were selected for decay testing.

The soil-bed chamber was set to 25°C and 80% RH to promote active growth of decay fungi at the wood/ground/air interface. Stakes were installed in a random order 75 mm apart from one another. One daughter stake was installed in a bed of soil from the Malcolm Knapp Research Forest, maintained at greater than 60% water holding capacity, to favour the growth of basidiomycetes. After six months, 15 x 15 x 60 mm white spruce mini-stakes infected with *Leucogyrophana pinastri* Findlay 141 and *Fibroporia radiculosa* L-7878-Sp were added to the forest soil bed. Infected mini-stakes were inserted approximately 50 mm into the soil in a staggered array between all stakes, such that each test stake was approximately 50 mm from two *F. radiculosa*-infected mini-stakes and two *L. pinastri*-infected mini-stakes. The other daughter stake was installed in a commercial planter box soil bed (Vanttro), maintained at greater than 90% water holding capacity, to favour the growth of soft-rot fungi.

Samples were inspected for decay as specified in AWPA E14-07 after 6, 12 and 17 months.

Table 1. Preservative Formulations Evaluated in AWPA E14 Soil Bed Decay Test

Formulation	Description
A	6.4 kg/m^3 ACQ (reference)
B	CBP1 – low retention
C	CBP1 – medium retention
D	CBP1 – high retention
E	Additive 1
F	CBP1 (medium) + Additive1
G	CBP1 (medium) + Additive 2
H	Additive 2
I	CBP2 A – low retention
J	CBP2 A – medium retention
K	CBP2 A – high retention
L	CBP2 B – low retention
M	CBP2 B – medium retention
N	CBP2 B – high retention
O	CBP2 C – low retention
P	CBP2 C – medium retention
Q	CBP2 C – high retention
R	CBP2 D – low retention
S	CBP2 D – medium retention
T	CBP2 D – high retention
U	Untreated (control)

<u>2.2 Microbial Community Characterization</u>

A second soil-bed test was initiated according to AWPA E14-07 (AWPA 2014a). Fifteen stakes treated with the formulations listed in Table 2 were prepared in the manner described above. One set of daughter stakes was used for decay evaluation, the other set was destructively sampled for extraction of DNA and analysis of preservative retention. All stakes were installed in commercial planter box soil bed to favour the growth of soft-rot fungi. Soil moisture content was cycled between saturation and 90% water holding capacity using a spray system controlled by a Toro XTRA SMART™ precision soil moisture sensor.

Table 2. Preservative Formulations Evaluated in AWPA E14 Soil Bed Decay Test

Formulation	Actives
Untreated (control)	N/A
CBP1	Triazole(s), quaternary ammonium compounds
CBP2	Triazole(s), quaternary ammonium compounds
ACQ-D	Copper, quaternary ammonium compounds

Three depletion stakes from each treatment group were removed from test after 2, 4, 8, 16, and 32 weeks of incubation. Stakes were wrapped in plastic bags and frozen at -20°C until ready for further processing. Analysis biscuits were cut 90 mm below the groundline. Samples obtained after 32 weeks of exposure were analyzed for quaternary ammonium compounds and/or tebuconazole and/or propiconazole, as appropriate, along with the unexposed biscuits. Quaternary ammonium compounds were measured by LC/MS based on the methods of Stirling *et al.* (2010). Triazoles were measured by HPLC using a method similar to AWPA A48-09 (AWPA 2014b). Major deviations from this method included the use of a Phenomenex Gemini 5µm C18 110 Å 250 x 4.6 mm column, addition of 0.1% phosphoric acid and 0.5% acetonitrile to the mobile phase, and maintenance of the column temperature at 40°C.

Ten millimetre cross-sections were sawn from each stake 50 mm below and 50 mm above where the preservative depletion sample was taken. A sterile razor blade was used to remove 3 mm of wood from three sides of each block. A 1 mm slice was then taken from the exposed interior of the stake. One millimetre was cut and removed from the top and bottom of each sample. The samples were chopped into thin slivers and approximately 0.2 g placed into a 1.5mL tube. In addition, one surface sample was taken for DNA extraction from each group of stakes. Samples were frozen at -20°C before DNA extraction. Samples were ground in liquid nitrogen with a mortar and pestle and 0.1 g of frozen wood was mixed with 800 µl 2% CTAB buffer amended with 1% beta mercaptoethanol. The slurry was incubated for 30 min to one hour at 65°C and then centrifuged at 15000 x g for 3 minutes. The supernatant was then cleaned using the Promega Wizard SV genomic DNA purification kit, following the manufacturer's instructions. The three DNA samples from each treatment group in each time frame were combined to make one DNA sample representing the three treatment replicates.

DNA was sent to McGill University and Genome Quebec Innovation Center for Illumina sequencing. DNA of bacteria and fungi were amplified separately, targeting the V3 - V4 region of the 16S ribosomal gene for bacteria and the internal transcribed spacer 1 (ITS 1) for fungi. The bacteria were amplified with the primers S-D-Bact-0341-b-S-17 and S-D-Bact-0785-a-A-21 (Herlemann *et al*. 2011) at an annealing temperature of 50°C. The ITS1 for the fungi was amplified using the primers ITS1F (Gardes and Bruns 1993) and 58A2R (Martin and Rygiewicz 2005) at an annealing temperature of 52°C. Bovine Serum Albumin (BSA) was added to all reactions at a concentration of 0.3 μg/μl. A unique barcode and sequencing primers were attached to the end of each sample in a second amplification. All fungal samples were pooled together, and all bacterial samples were pooled, and 250 paired end libraries were prepared and sequenced on the Illumina MiSeq platform.

DNA sequence data was analyzed using the QIIME software package (Caporaso *et al*. 2010a). Paired ends were joined using a minimum overlap of six base pairs and a five percent maximum difference. Quality filtering and barcode removal was done using the default parameters except for the Phred quality score which was set to a minimum of 20. Open reference operational taxonomic unit (OTU) picking was done using the UCLUST sequence clustering algorithm (Edgar 2010) for both fungi and bacteria. For the bacterial 16S sequences, sequences were aligned to the Greengenes core reference alignment (DeSantis *et al*. 2006) using the Python Nearest Alignment Space Termination (PyNAST) tool (Caporaso *et al*. 2010b). Taxonomy was assigned using the Greengenes database version 13_8 (McDonald *et al*. 2012) using the Ribosomal Database Project (RDP) Classifier 2.2 (Wang *et al*. 2007). For the fungal ITS1 sequences, taxonomy was assigned using the UNITE database (Abarenkov *et al*. 2010) and the Basic Local Alignment Search Tool (BLAST) (Altschul *et al*. 1990).

Operational taxonomic units (OTUs) were used to refer to representative sequences clustered at the 97% identity level. Identification to species or genus was based on the closest sequence matches during the taxonomic assignment. Sequences and closest identity may not necessarily represent actual species or actual species identification. Only samples taken from 3 mm below the surface were considered in the analysis.

3. Results and Discussion

3.1 Initial Evaluation of Modified Carbon-Based Preservatives

After 17 months of exposure, all of the untreated stakes had failed in the forest soil (Figure 1). In contrast, the ACQ-treated reference had no confirmed decay (one stake was rated 9.5 for suspicion). A dose response was evident for CBP1 (Formulations B-D), though even the highest concentration evaluated (Formulation D) had confirmed decay in nine of ten samples. Average decay ratings for formulations with additives to CBP1 (Formulations F and G) were not significantly different than the equivalent retention of unmodified CBP1 ($p < 0.05$). Average decay ratings for stakes treated with one of the additives (Formulation E) were significantly higher than untreated controls, though decay was still well advanced in these samples. Average decay ratings for stakes treated with the second additive (Formulation H) were not significantly different than the untreated controls ($p < 0.05$). A dose response was evident for CBP2 (Formulations I-K) and it had similar performance to CBP1 at comparable retentions. The modifications made to CBP2 had little effect. All groups, except the ACQ-treated reference, exhibited confirmed decay after 12 months in test.

The absence of decay in any of the stakes at six months, followed by steadily progressing decay in most groups after 12 and 17 months, suggests that the inoculation of the soil bed with *L. pinastri* and *F. radiculosa* after six months may have accelerated decay, or this may instead be due to the time required for detoxifying organisms to reduce preservative concentrations. These fungi were observed to grow through the soil to a limited extent, but decay in the stakes was not analyzed to determine whether it was associated with these fungi.

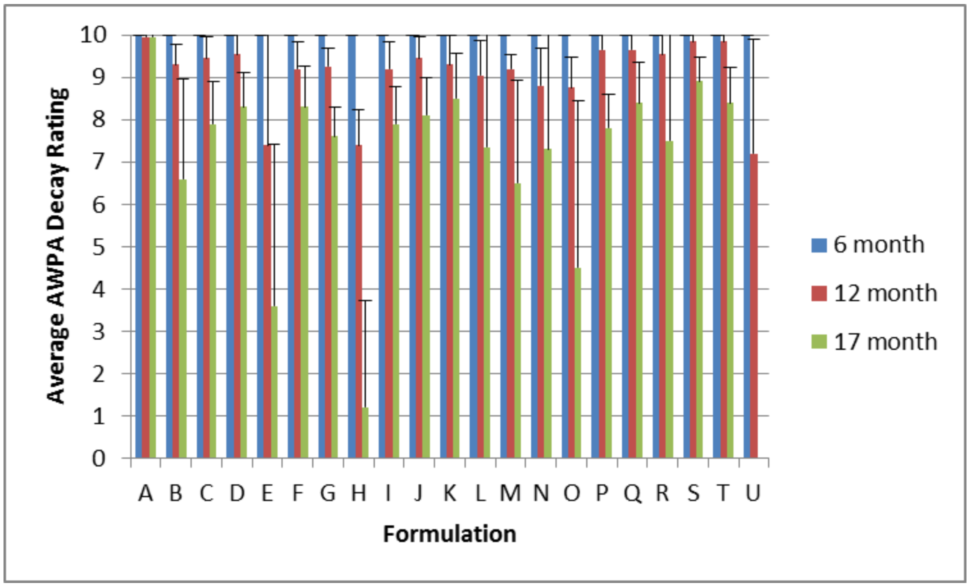

Figure 1. Average decay ratings in the basidiomycete bed

Decay was more rapid in the soft-rot soil bed (Figure 2). Untreated controls had an average decay rating of 2.8 after 12 months and had completely failed after 17 months. The ACQ-treated reference was by far the best performer, though 30% of samples had confirmed decay after 12 months and 90% of samples had confirmed decay after 17 months. After 17 months all stakes had failed, with the exception of those treated with ACQ, and two stakes treated with a modified version of CBP2 (Formulation S) that were rated 7 for decay.

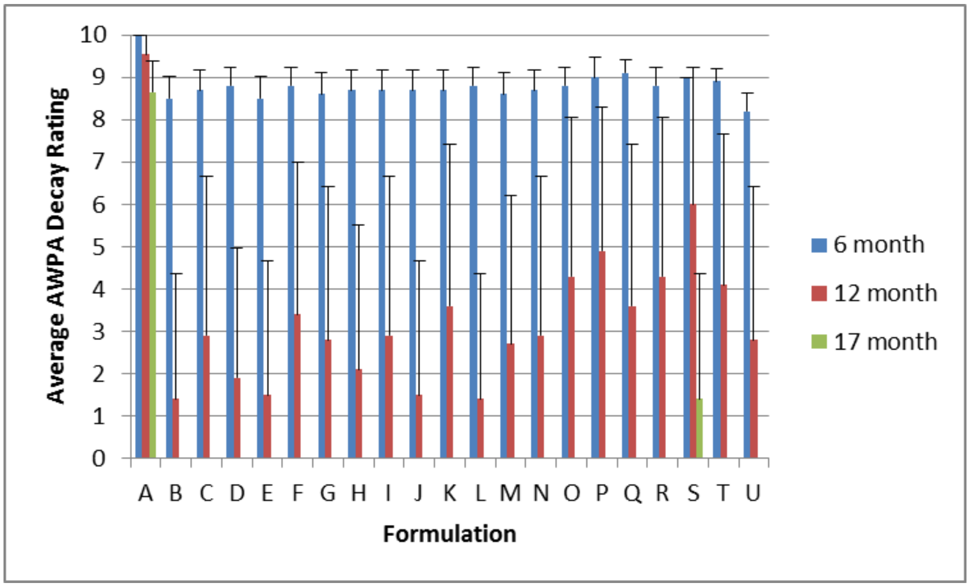

Figure 2. Average decay ratings in the soft-rot bed

3.2 Microbial Community Characterization

Average decay ratings after 32 weeks confirmed an aggressive test. Untreated controls were moderately to severely degraded with an average rating of 6.3 on the AWPA Scale, including three failures. All carbon-based preservatives showed some signs of decay with average ratings ranging from 8.7 to 8.9. The reference preservative, ACQ-D, remained sound. After 64 weeks most untreated controls had failed and there was substantial decay in both CBP formulations with multiple failures in each group. The ACQ-D reference was still performing well, with an average rating of 9.6. This again highlights the efficacy of copper in ground contact.

Table 3. Average Decay Ratings after 32 and 64 Weeks of Exposure

Formulation	Active Ingredients	Average AWPA Decay Rating (32 weeks)	Average AWPA Decay Rating (64 weeks)
Untreated	N/A	6.3 (3.3)	1.6 (3.1)
CBP1	Triazole(s), quaternary ammonium compounds	8.9 (0.6)	4.3 (3.6)
CBP2	Triazole(s), quaternary ammonium compounds	8.7 (0.6)	2.8 (3.5)
ACQ-D	Copper, quaternary ammonium compounds	10 (0)	9.6 (0.7)

Azoles showed no evidence of depletion after 32 weeks of exposure from CBP1, CBP2, or the ACQ reference (Figure 3). The ACQ reference was not intended to contain azoles; however, tebuconazole was detected in these samples. This was traced back to contamination during the treatment process. In contrast, DDAC concentrations were lower in samples taken after 32 weeks of exposure in all samples. Average depletion ranged from 23 to 66% of initial values. It is not known whether this depletion was due to leaching or detoxification.

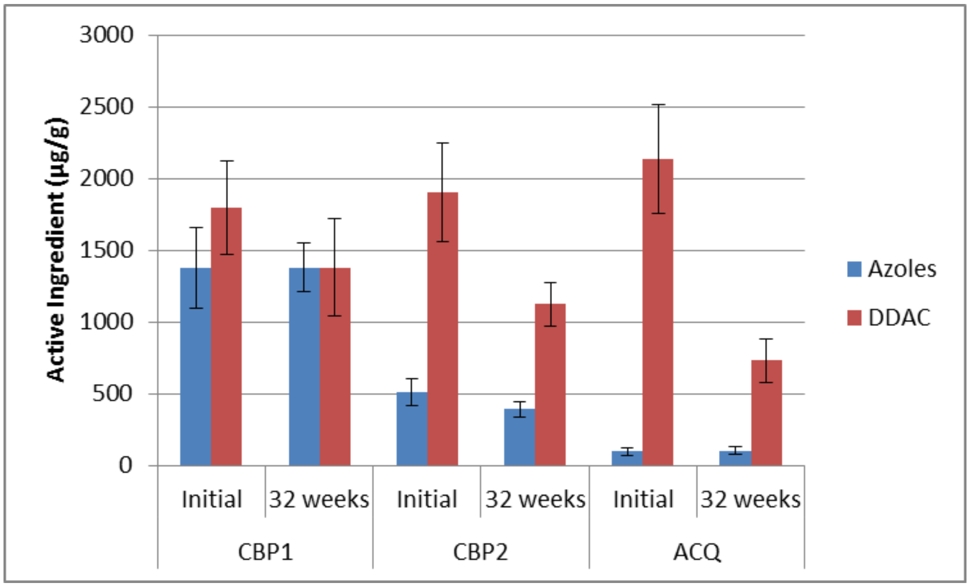

Figure 3. Depletion of azoles and DDAC after 32 weeks of soil exposure

DNA barcoding revealed 609 unique bacterial OTUs and 149 unique fungal OTUs present in at least one of test stakes. One and a half to two times more species were detected in wood treated with carbon-based preservatives than in wood treated with ACQ. Overall there were 11 fungi and 12 bacteria present on the majority of CBP-treated samples, but not present on the ACQ reference.

Most bacterial OTUs could not be identified to the species level, and many could not be identified to the genus level. *Pseudomonas* was the most common genus (family Pseudomonadales), and was found on all samples in all treatments. Sphingomonadaceae and Comamonadaceae were the second most common families found on 39 of the 40 samples.*Pseudomonas* spp. and other proteobacteria have previously been associated with carbon-based preservative degradation (Wallace and Dickinson 2004).

Figure 4 shows the number of bacterial OTUs per sample at each time frame. Interestingly, for the two CBP treatments, there was not a clear increase in the number of OTUs with increasing exposure time. The ACQ-D showed an increase in OTUs over time with the samples taken from the 40 mm below ground portion of the wooden stake and the untreated samples showed an increase over time for both sets of samples. It appears that while the CBP stakes are rapidly colonized by all the bacteria that can tolerate them, it takes longer for the conditions to be conducive in the ACQ stakes. The untreated stakes can support a much wider range of species.

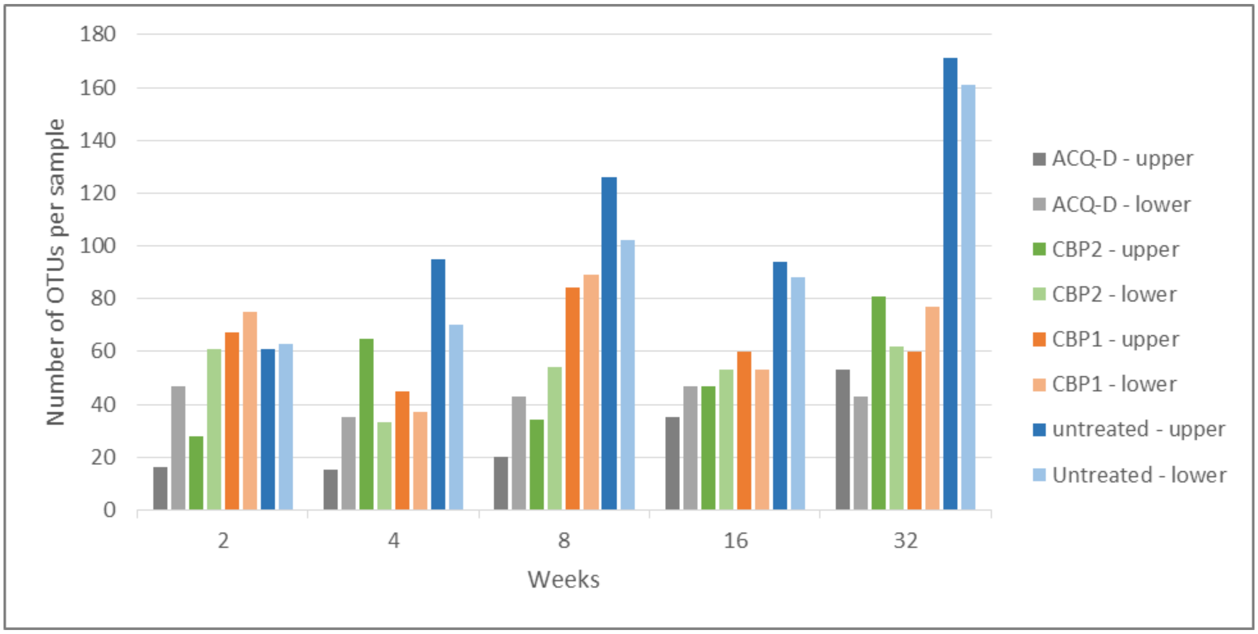

Figure 4. Number of Bacterial OTUs found on each treatment group at each sampling time on the 40 mm below ground and the 140 mm below ground samples

Twenty-nine percent of the fungal sequences could not be identified beyond kingdom. Sixty-two percent were Ascomycota and 8% were Basidiomycota. Most fungal OTUs were found on only one sample per treatment. No particular fungal species was associated with all samples in a treatment group. An OTU most closely matching *Ceratocystis fimbriata* was the most frequently found OTU and was present in all but ACQ-treated samples. Basidiomycete fungi were associated with untreated and CBP-treated samples, but not with ACQ-D-treated samples.

Figure 5 shows the number of fungal OTUs per sample at each time frame. There was no clear trend showing an increase in the number of OTUs over time; however the data suggest a peak in fungal diversity between four and 16 weeks, particularly evident in the untreated samples.

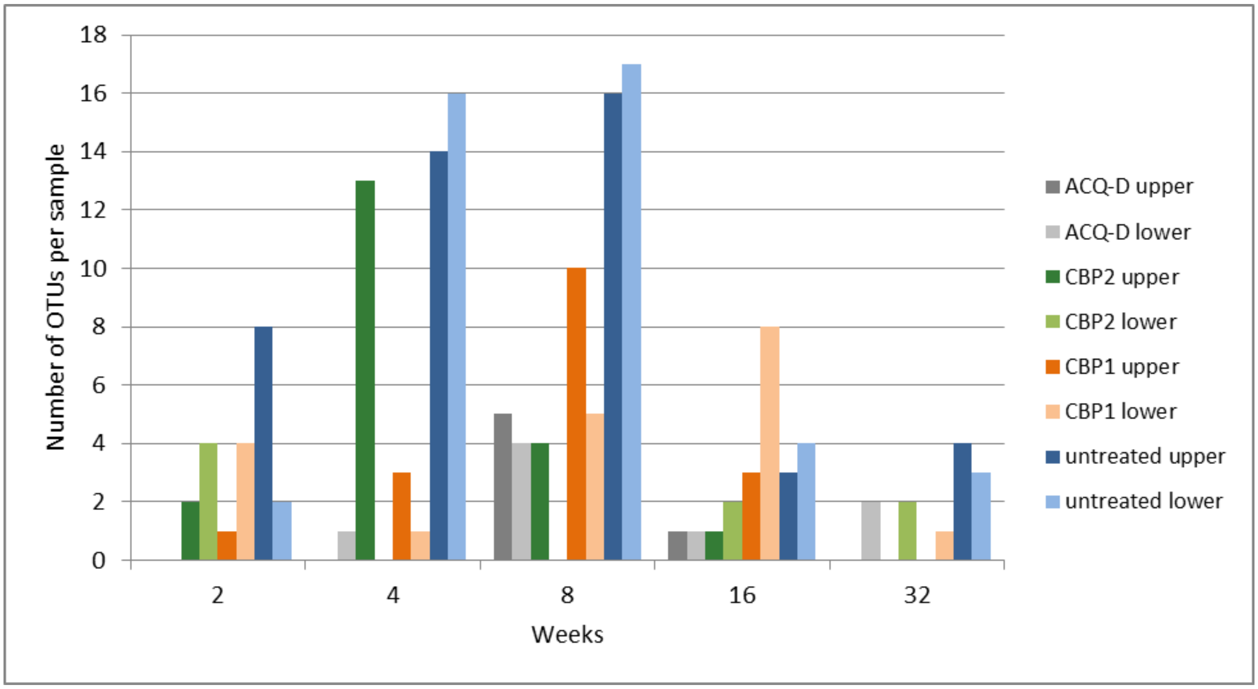

Figure 5. Number of Fungal OTUs found on each treatment group at each sampling time on the 40 mm below ground and the 140 mm below ground samples

Further analysis of the microbial community data will be described in a manuscript currently in preparation.

4. Conclusions

None of the selected modifications significantly improved the decay resistance of carbon-based preservatives used in ground contact.

None of the modified carbon-based preservatives performed as well as the ACQ-treated reference in ground contact.

DNA barcoding identified 11 fungi and 12 bacteria present on the majority of CBP-treated samples, but not present on the ACQ reference. Future work should investigate means of controlling these organisms.

5. Acknowledgements

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COPPER NAPHTHENATE TREATED WOOD – A REVIEW AND REGULATORY UPDATE

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SUMMARY

Copper naphthenate (CuN) is a wood and textile preservative that has equivalent efficacy yet lower mammalian toxicity compared to other heavy duty preservatives. CuN-treated wood has a clean surface, is non-conductive, and has good lubricating and waterproofing qualities. CuN in heavy oils such as #2-diesel or AWPA HSA solvent is currently used for pressure treatment of utility poles, railroad crossties and bridge ties & timbers, posts, piles and glulam beams. It is suitable for overtreatment of wood previously treated with waterborne borate formulations as a dual treatment of ties and poles.

1. INTRODUCTION

Copper naphthenate is produced by the reaction of naphthenic acid and copper compounds. Naphthenic acid is the carboxylic acid component naturally occurring in petroleum, classified as monobasic carboxylic acids of the general formula RCOOH, where R represents the naphthene moiety consisting primarily of cyclopentane and cyclohexane derivatives. Pure copper naphthenate is a glassy, amorphous solid or paste containing 11-13% Cu metal equivalent depending on the molecular weight of the parent naphthenic acid. Naphthenic acid is ideal for synthesizing metal carboxylates that require a ligand with oxidative stability, solubility in hydrocarbons and oils, and insolubility in water (Brient et al. 1995).

CuN has been used as a preservative for wood, textiles and other cellulosic materials since the early 1900s, and was standardized by the American Wood Protection Association (AWPA) in 1948. It is primarily produced as an oil-borne concentrate containing 8% copper (as metal) and formulated in #2-diesel fuel, mineral spirits, or heavier oils. Waterborne formulations containing 5% copper have been produced as emulsifiable concentrates or alkanolamine-solubilized solutions; the waterborne formulation was standardized by AWPA in 2004.

CuN is supplied to pressure treaters as a concentrate which is diluted in oil-type solvents for heavy duty applications. Waterborne concentrates are diluted with water prior to treatment. Work solutions typically contain 1% ± 0.5% Cu. Treating cycles for CuN are similar to those used for pentachlorophenol in terms of pressure and temperature; treating temperatures are typically lower than those used for creosote since the CuN solution is less viscous at ambient temperature. Green wood may be steam conditioned or Boulton seasoned prior to CuN treatment, although air seasoning and kiln drying are more widely used. A post-treatment steaming operation is recommended to remove residual CuN work solution from the wood surface as specified in Best Management Practices (WWPI 2012), which are US and Canadian recommended guidelines for the production and use of treated wood products in aquatic and other sensitive environments to enhance the environmental and aesthetic aspects while maintaining performance.

2. REGULATORY STATUS

Copper naphthenate is not a restricted use pesticide (RUP), but is instead classified by the US EPA as a General Use pesticide due to its lower toxicity categories. Table 1 compares the US EPA classification and other regulatory limits for CuN (as Cu) and the two other oil-borne heavy duty wood preservatives creosote and pentachlorophenol. EPA established Regional Screening Levels (RSL) for various pollutants in tap water and residential soil, including copper (but not CuN or naphthenic acid), pentachlorophenol, and the various polynuclear aromatic hydrocarbons (PAHs) that comprise the majority of creosote. Allowable RSLs for Cu in water and soil are 3-4 orders of magnitude greater than for penta or naphthalene, the primary PAH in creosote. Because of its low toxicity rating, CuN is the only one of these three heavy duty preservatives to be registered for sell over the counter for consumer/residential use by both PMRA and US EPA as a wood and material preservative. CuN is not currently registered by the European Union/ECHA Biocidal Products Regulation as an active ingredient for PT8: Wood Preservatives.

Table 1. Wood Preservative Comparison – US EPA Classifications

	Copper Naphthenate	Creosote	Pentachlorophenol
Classification	General Use	Restricted Use	Restricted Use
Toxicity Category	III	I	I
RCRA Listed Hazardous Waste	Not listed	F034, K001, K035, U051	F021, F027, F028, F032, K001
CERCLA Reportable Quantity (RQ), lbs.	No RQ	1	10
OSHA Select Carcinogen	Not listed	Yes	Yes
Tap Water RSL, µg/l	620 Cu	0.17 Naphthalene	0.17
Residential Soil RSL, mg/kg	3100 Cu	3.8 Naphthalene	0.89

There are currently 12 active EPA registrations for CuN products in the US, including 8 oil-borne formulations and 4 waterborne formulations. The 8% Cu oil-borne concentrate contains 68% CuN, while the 5% Cu waterborne concentrate contains 45.4% CuN. Other registered products include ready-to-use formulations containing 1% - 2% Cu in both oil-borne and waterborne formulations, and pastes/wraps containing 2% Cu. There are currently 21 active PMRA registrations for CuN products in Canada, including 3 oil-borne (8 – 8.15% Cu) and one waterborne (5%) commercial concentrate products. PMRA labels specify only % Cu and do not list copper naphthenate content.

All 15 of the ready to use products are oil-borne formulations for either domestic/residential use by brush application or commercial use by brush, dip, or spray application. Two oil-borne CuN wraps containing 2% Cu and one waterborne CuN wrap containing 1.6% Cu (with 38.98% DOT borate) are also registered.

As for all pesticides, the US EPA reviewed the available data for CuN as part of a Re-registration Eligibility Decision (RED) in 2007. Certain data gaps were identified in the RED data call-in, mostly involving aquatic toxicity, and those studies have since been completed. The American Chemistry Council's Antimicrobial Exposure Assessment Task Force (AEATF II), of which Nisus is a full member, is currently conducting the worker exposure study required as part of the data call-in. A follow-up Registration Review was conducted in 2010, when EPA concluded no additional data would be needed. A final decision was due in 2015 but is still pending. A similar PMRA Re-evaluation Decision (RVD) was conducted recently for CuN, including a science evaluation in 2010 and final RVD 2011-07 in October 2011 that granted the continued registration of products containing CuN for sale and use in Canada. The review found that continued use of CuN does not present an unacceptable risk to human health or the environment.

3. CSA & AWPA STANDARDS

CuN is adopted as a standardized wood preservative by the Canadian Standards Association (Standard O80-15), and more widely by the American Wood Protection Association. Tables 2 – 5 summarize minimum retentions for CuN (as Cu metal) for a variety of commodities and wood species.

Table 2. CSA O80.1-15 Standard for CuN-treated Crossarms & Poles Minimum retention standards, kg/m^3 [lbs/ft^3], as Cu			
Service	Southern Pine	Douglas-fir	Western Red Cedar
UC3.1/3.2 (crossarms)	0.64 [0.040]	0.64 [0.040]	Not listed
UC4.1	1.3 [0.08]	1.5 [0.09]	1.9 [0.12]
UC4.2	2.1 [0.13]	2.4 [0.15]	1.9 [0.12]

Table 3. AWPA U1-16 Standard for CuN-treated Crossarms & Poles Minimum retention standards, kg/m^3 [lbs/ft^3], as Cu			
Service	Southern Pine	Douglas-fir	Western Red Cedar
UC3B (crossarms)	0.64 [0.040]	0.64 [0.040]	0.64 [0.040]
UC4A	0.96 [0.060]	1.2 [0.075]	1.92 [0.12]
UC4B	1.28 [0.080]	1.52 [0.095]	1.92 [0.12]
UC4C	2.1 [0.13]	2.4 [0.15]	1.92 [0.12]

Table 4. CSA O80.1-15 Standard for CuN-treated Posts & Crossties Minimum retention standards, kg/m^3 [lbs/ft^3], as Cu				
Service	Southern Pine	Douglas-fir	Oak/Hickory	Mixed Hardwoods
Posts, UC4.1	0.88 [0.055]	0.88 [0.055]	--*	--
Post, UC4.2	1.3 [0.08]	1.5 [0.09]	--	--
Ties, UC4.1/4.2	Not listed	Not listed	Not listed	Not listed

* No hardwoods are included in CSA O80.1 for posts

Table 5. AWPA U1-16 Standard for CuN-treated Posts & Crossties Minimum retention standards, kg/m^3 [lbs/ft^3], as Cu				
Service	Southern Pine	Douglas-fir	Oak/Hickory	Mixed Hardwoods
Posts, UC4A	0.88 [0.055]	0.88 [0.055]	--*	--
Post, UC4B	1.1 [0.069]	1.1 [0.069]	--	--
Ties, UC4C	0.96 [0.060]	0.96 [0.060]	0.88** [0.055]	0.96 [0.060]

* No hardwoods are included in AWPA U1 for posts ** Or to refusal

4. COMMODITIES & USES

The major application for CuN in the US is in heavy duty pressure treatment applications including utility poles, crossties and switch ties, bridge timbers, fence posts, piles, and highway construction projects such as pedestrian and automotive bridges, sound barrier walls, and salt storage buildings. Environmental and performance considerations are prompting the expanded use of CuN for treatment of railroad bridge ties and timbers (Brient 2015). Dual treatment of ties with disodium octaborate tetrahydrate followed by CuN is increasingly being specified by railroads to give enhanced performance. Other significant uses in both the US and Canada include non-pressure applications for remediation of utility poles and field cut/end cut treatments for both commercial and domestic/residential uses.

5. EFFICACY & PERFORMANCE STUDIES

CuN has been used effectively as a wood preservative since the early 1900s, and exhaustive lab and field studies have been conducted to demonstrate its efficacy. The US Department of Agriculture's Forest Products Lab began an extensive field study in the late 1930s using ~5" (~125 mm) diameter southern pine posts treated with a variety of preservatives (Davidson 1977). Freeman et al. (2005) updated that 1977 FPL report to estimate service life of the posts, as approximated by the 60th percentile, after a further 23 years of exposure. A pass-fail system utilized a 50 lb (23 kg) lateral pull at the top to test for failure at the ground line. Table 6 shows that CuN gave better performance in terms of estimated service life than creosote and penta after a total of 53 years of exposure in an AWPA Hazard Zone 5 site. Particularly notable is the fact that the Cu retention was only 23% of the AWPA minimum specified for poles in that hazard zone (UC4C), compared to creosote and penta treated to ~66% of their AWPA retention minima.

Table 6. Estimated service life from FPL-RN-01			
Treating Solution	Retention, kg/m^3 [lbs/ft^3]	Retention, % of APWA U1 minimum	Estimated average life, years
Untreated control	--	--	2.4
Carrier oil	96.0 [6.0]	--	7.7
CuN, 0.5% Cu	0.48 [0.03]	23	65.2
Penta, 5.0%	4.8 [0.30]	67	55.5
Creosote	94.4 [5.9]	66	45.7

Results from the latest FPL-RN-02 field study update (Woodward 2011) are summarized in Table 7, showing comparable efficacy of CuN to creosote and pentachlorophenol using nominal 2- x 4- x 18-inch (38 x 89 x 457 mm) southern pine stakes installed in Mississippi and evaluated after 51 years. All samples were treated to ~64 kg/m^3 (4 lb/ft^3) net solution retention, with concentration of active ingredients varied to provide multiple AI retentions. Again, CuN gave equivalent or better performance than competitive preservatives even when treated to a smaller fraction of its AWPA minimum retention.

Table 7. FPL-RN-02, Table 17			
Treating Solution	Retention, kg/m^3 [lbs/ft^3]	Retention, % of APWA U1 minimum	Estimated average life, years
Untreated control	--	--	2.2
Carrier oil	64.0 [4.0]	--	7.6
CuN, 0.5% Cu	0.34 [0.021]	28	14.3
CuN, 0.75% Cu	0.53 [0.033]	44	17.4
Penta, 5.0%	3.36 [0.21]	42	14.2
Creosote	65.6 [4.1]	41	16.3

Waterborne copper naphthenate (CuN-W) is also an effective wood preservative that is mostly used for non-pressure applications such as dip treatment of boxes and spray treatment of roofing shakes and shingles. The lack of a water-repellent solvent carrier oil results in slightly reduced efficacy for CuN-W vs. CuN on a Cu retention basis, particularly at low Cu retentions. Figure 1 summarizes field stake ratings of 19 x 19 mm (3/4-in x ¾-in) southern pine stakes installed in Mississippi, where highest Cu concentration treating solutions give comparable performance after 11 years' exposure whether waterborne or oil-borne ("CuN-O" in Figure 1). AWPA Standard U1 reflects this performance difference, assigning minimum retentions for southern pine lumber in ground contact (UC4A) at 0.96 kg/m^3 Cu (0.060 lb/ft^3) for CuN vs. 1.76 kg/m^3 Cu (0.11 lb/ft^3) for CuN-W.

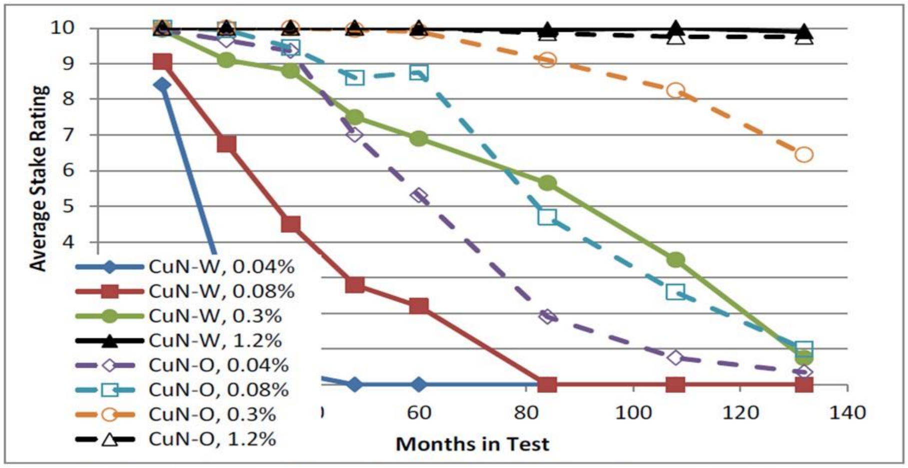

Figure 1. Stake test results for oil-borne and waterborne copper naphthenate

"Climbability" is a property of great interest to utility linemen who must climb poles during installations and maintenance work. Oil-borne preservatives such as CuN have the advantage over waterborne preservatives in that the oil lubricates and softens the exterior of the poles to facilitate gaff penetration. The force required for a gaff to penetrate southern pine and Douglas-fir pole stubs was equal to or less than other oil-type preservatives and untreated wood (Shupe 2011), as shown in Figure 2.

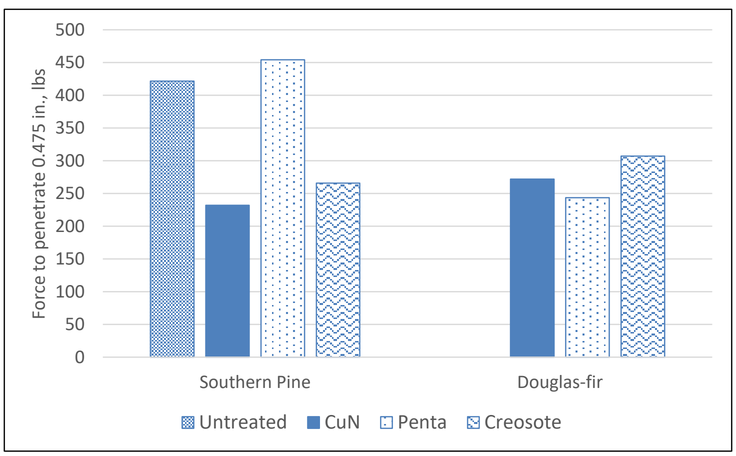

Figure 2. Penetration, force required for 9206 gaff

Conductivity of treated wood is also a concern in both utility poles (potentially "hot" or energized poles) and railroad switch ties (possible interference with signaling). Although one might presume CuN is conductive due to the presence of copper, in fact the opposite is the case. Ragon et al. (2010) measured the conductivity of untreated and treated wood samples with similar moisture content. Figure 3 shows that CuN-treated wood acts as an insulator, with equivalent conductivity (in micro-Siemens per cm) to untreated wood and significantly less conductivity than penta and

CCA-treated wood, which have 211 and 293 times the conductivity of CuN-treated wood, respectively.

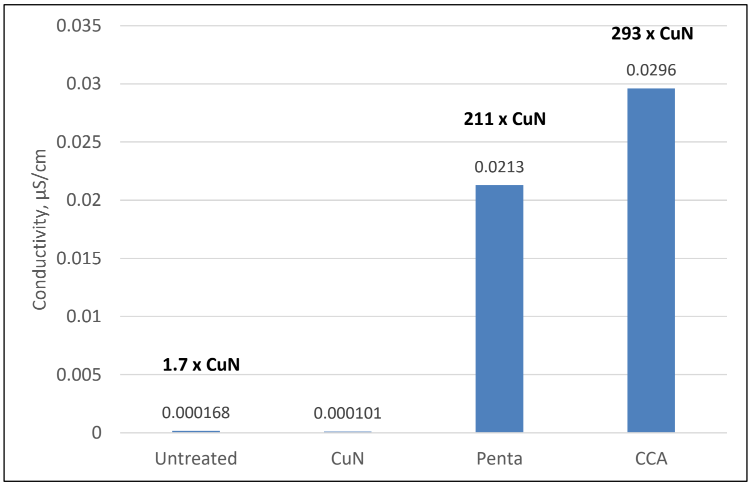

Figure 3. Conductivity of treated and untreated wood

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Release of Copper from Micro Cu Pressure Treated Wood

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ABSTRACT

Micronized copper based wood preservatives including micronized copper quat (MCQ) and micronized copper azole (MCA) have been introduced commercially to the North American market since 2006 as alternatives to alkaline copper quat (ACQ) or soluble copper azole (CA) preservatives. Unlike ACQ or CA, MCQ and MCA use dispersed particulate copper particles rather than soluble ionic copper to make treating solutions for pressure treating wood (PTW). The use of particulate copper for PTW raises questions about the potential exposure of copper or copper particles to the environment. Common pathways of exposure include leaching during contact with rain water, physical contact during handling, and airborne contact during sawing of PTW at job site. This paper reviews and reports a few studies on the release of copper from MCA or MCQ treated wood during water leaching and wiping. In addition, a sawing study of PTW to determine airborne copper particles is also reported. In all the studies, the soluble copper preservatives, ACQ-D or CA-B were used as reference control.

The water leaching studies indicated that wood treated with micronized copper preservative systems has substantially less copper leached than wood treated with soluble copper preservatives, resulting in a much lower potential impact on the environment. For the micronized copper treated wood, greater than 95% copper leached from PTW is in ionic form. Only small amount of copper leached is in particulate form. In addition, the particulate copper released is not in free copper form, but rather attached to wood cellulose substrate. The results from wipe test indicate that both MCA and its soluble counterpart CA released approximately the same amount of copper with each contact. In both cases, the level of copper released high initially and then levelled off after 2-3 wipes. The sawing study indicated that the total copper release from PTW during sawing at job site is negligible. Majority of copper particles in the collected air samples during sawing were embedded in wood matrix, and only occasional free copper particles were found.

Keywords: Micronized Copper, Soluble Copper, Particulate Copper, MCQ, MCA, Wipe, Leaching, Sawing.

1. INTRODUCTION

Micronized copper wood preservatives are based on a novel copper technology and are widely used in today's North American wood preservation market. Unlike the traditional alkaline copper preservatives where copper is solubilized in aqueous ethanolamine solution, micronized copper formulations do not use the organic solvent mono-ethanolamine. Instead, sparsely water soluble copper compounds, such as basic copper carbonate, are "micronized" into particulates and dispersed in water instead of using water soluble forms of copper compounds or complexes. There are currently two commercially available micronized copper systems, namely micronized copper quat (MCQ) where dimethyldidecylammonium carbonate/bicarbonate is used as a co-biocide, and MCA where either tebuconazole or a tebuconazole/propiconazole combination is used as a co-biocide. However, since its commercial introduction in 2007, MCA has become the dominant micronized copper preservative in North America.

Numerous studies have been reported on laboratory and field performance of micronized copper preservatives against wood decay fungi and termites. Zhang (2015) reported over 10-years field efficacy of stakes treated with MCA, and the results indicated that MCA performed at least as well as the reference preservative systems of ACQ and CA-B. Larkin *et al.* (2008) reported on the biological performance of MCA and MCQ treated stakes exposed in ground contact in Hawaii for over 3 years, and concluded that MCA and MCQ performed similar to an alkaline copper quat system (ACQ-D). They further concluded that all field stakes with retentions at or above the commercial loadings for ground contact applications were performing very well with little or no decay damage. In Australian field trials on the efficacy of micronized copper system. Cookson *et al.* (2008) reported on the biological efficacy of micronized copper against termites and decay fungi, and concluded that MCQ and ACQ performed similar in an in-ground stake trial. They also reported on a laboratory soil block test which showed that MCQ and ACQ gave similar performance against four brown rot and two white rot fungi. They further reported that MCQ performed similar to ACQ against two aggressive subterranean termites, *Coptotermes acinaciformis* and *Mastotermes darwiniensis,* in an H3 (outside, above-ground) field test. In a comprehensive review of all the copper based wood preservatives, Freeman and McIntyre (2008) reviewed over a dozen laboratory and field exposure studies focusing on the biological performance of micronized copper preservative systems, and concluded that micronized copper formulations perform as well or better than their amine-solubilized counterparts against termites, brown rot, white rot and soft rot fungi. In an attempt to address the mechanism of action of micronized copper preservatives, Zhang and Ziobro (2009) conducted a 20-week water leaching study, and the result showed the micronized copper in treated wood continuously released cupric ion when exposed to water and the level of cupric ion released is similar to that of amine soluble copper counterpart, and slightly higher than CCA preservative. Additional results of laboratory and field tests were reported by Zhang and Ziobro (2010) and McIntyre et.al (2012) which again demonstrated the effectiveness of MCA against wood destroying organisms

The presence of particulate copper in the pressured treated wood (PTW) raises questions about the potential environment and human exposure to the particles. Common pathways of exposure include leaching during contact with rain water, physical contact during handling, and airborne contact during sawing of PTW at job site. This paper reviews several studies on the release of copper using water leaching test and wipe test. In addition, a sawing study of PTW to determine airborne copper particles is also reported.

2. WATER LEACHING STUDY

2.1 Water Leaching Study #1

Zhang and Ziobro (2009) conducted a 20-weeks water leaching study on 19mm wood blocks treated with micronized copper MCA and MCQ preservatives. In addition, two water soluble copper preservatives, ACQ-D and Copper Chromated Arsenate (CCA) were also used as a reference system. AWPA E11-06 water leaching protocol was followed for the leaching study. Each set of the treated wood blocks were submerged in 300ml deionized water, and after six hours, the leachate water was removed from each sample and replaced with 300ml fresh DI water. The leaching water was exchanged as above after 1d, 2d, 3d, 6d, 8d, 10d and 13d intervals and thereafter weekly change for a total of 20 weeks, and the leachate samples were taken for each exchange. Immediately after each leachate was collected, two 20-ml samples were taken for chemical analysis. The first 20 ml sample was analyzed for copper without acid modification, and the second 20ml sample was acidified with concentrated nitric acid to pH about 1.0 and then analyzed for copper. The non-acidified analysis was to analyze all the soluble copper species, and the acidified analysis was to capture all copper species including soluble and insoluble particulate copper species. The results were presented in Figures 1 - 4. Based on the results, the following observations were made:

- Among all the preservatives, ACQ-D demonstrated the greatest copper release rate during the first few water leaching cycles, and started to level off. Overall, CCA showed the least amount of copper leaching.
- MCA and MCQ also showed relatively higher copper leaching rate at the initial leaching stage, however, the level of copper release was significantly lower than ACQ-D. In addition, the reduction in the leaching rate was less apparent than ACQ as the leaching cycles continued.
- The high level of copper in the non-acidified leachates indicated that the majority of copper leached is in the form of soluble form regardless of the preservatives studied.

2.1 Water Leaching Study #2

KPC sponsored Professor Dr. Paul Cooper at University of Toronto to conduct a research study which compared the copper leaching from four preservative systems, CCA, ACQ-D, MCA and MCQ. The following standardized and non-standardized protocols were used in the leaching study:

- AWPA E11 leaching protocol: 19mm southern yellow pine sapwood cubes were treated and submerged in de-ionized water for a period of 2 weeks.
- Organization for Economic Co-operation Development (OECD) Method I Leaching Protocol (Paul and Ung, 2008): Wood specimens with dimension of 20mm x 50mm x 15mm (Tangential x Longitudinal x Radial) were treated and end-sealed. The protocol recommends a one-hour immersion in water to simulate exposure to a rainfall event. Two "rainfall events" per day were used, and days of rainfall events are set for 1, 3, 5, 8, 10, 12, 15, 17, 19 days. The water samples were analysed for copper by ICP.
- OECD Method II Leaching Protocol (Paul and Ung, 2008): The same dimension samples as above were prepared by immersing the treated specimens in 500ml water with water exchanged after 6hours, 1 day, 2 days, 4 days, 8 days, 15 days, 22 days, and 29 days. The water samples were analysed for copper.
- Full Dimension Spray Exposure (above ground retentions only): Six 1.5 foot lengths of treated lumber were prepared from the lower retention lumber, end-sealed and assembled horizontally (on edge) over a collecting tray. Samples were sprayed with a fine misting spray that delivered a water volume of 5L/hour. Each day, the water volume was measured and removed and a leachate sample taken for analysis. The lumber was exposed without drying between cycles. The spray cycle was repeated daily for a total of 9 days. The leachate samples were collected and analyzed for copper.
- Full dimension Immersion Exposure (ground contact retentions only): The same dimension specimen were treated and submerged in trays of water with a similar surface

area to volume ratio as for OECD Method II. For each replicate test, 3 boards were placed in 25 liters of water and the water changed at intervals of 6 hours, 1 day, 2 days, 4 days, 8 days, 15 days, 22 days and 29 days. Leachate samples were collected and analyzed for copper.

The leaching results were given in Figure 5-7. The copper leached from preservative treated wood was computed as cumulative flux values mg copper per square meter (mg Cu/m^2). Based on the results, the following observations were made:

- The AWPA E11 leaching study demonstrated similar leaching results as those reported by Zhang and Ziobro (2009) where ACQ-D showed the highest copper leaching.
- Regardless the test protocol, ACQ-D showed the highest copper leaching. Both MCA and MCQ showed significantly lower copper leaching, and MCA showed slightly higher leaching than MCQ.
- The amount of copper leached varied considerably among the test protocols, however, the relative amount of copper leached from wood treated with the four formulations were consistent.

2.3 Water Leaching Study #3

United States Environmental Protection Agency (US-EPA) Office of Research and Development (ORD) conducted an independent leaching study of copper from PTW (EPA, 2014). Wood pressure treated with two types of MCA and an amine soluble copper azole (ACA) system at above ground retention and untreated wood were obtained from national hardware retailers within 50 miles of Cincinnati, OH area. For each PTW wood and untreated wood, two sample size were prepared with one as wood blocks and the other sawdust. Three different leaching solution, 0.01M NaCl (pH = 7), 0.01M NaNO3 (pH = 7) and Synthetic Water SPLP (pH = 4.2), and two different mixing duration (24 and 72 hours) were used. As a result, a total of 48 leaching scenarios were tested: 4 wood types x 2 specimen sizes x 3 leaching solutions x 2 mixing durations = 48.

After the mixing duration, the leachate solution was collected for copper analysis by ICP-OES. To determine the form of copper in the leachate solutions (soluble or particulate), the leachate solutions were pass through a serial of filters with large to small filter sizes. Approximate 10ml of the unfiltered leachate solution was used for the analysis of total copper leached. The remainder of the leachate solution was passed through 2.5 µm, 0.45 µm and 10 kDa filters, sequentially. After each filtration step, a 10ml sample was collected for copper analysis and the filter membrane was retained for acid digestion and copper analysis.

The total copper leached from wood when using SPLP leaching solution is given in Table 1. Table 2 shows the results of the total amount of copper released and the ionic fraction. The % particulate copper released and the fractions of particulate copper with each filter size is given in Table 3. EPA leaching study results indicated:

- MCA wood released significantly less copper than the soluble counterpart, leading to a lower potential impact on the environment.

- In comparison to the total copper released, both MCA and ACA showed very low level of particulate copper released with ACA showed slightly higher amount of particulate copper released.
- More than 95% of copper released from MCA wood is ionic copper form. In addition, majority of the particulates were captured by 2.5 µm filter membrane with significantly less particulates retained by the 0.45 µm and 10 kDa membranes. The small amount of particulate copper that was released is attached to cellulose fibre and is not free in solution.

3. WIPE STUDY

US-EPA ORD also conducted an independent wipe study on PTW (EPA, 2014). The wipe test protocol was developed by the Consumer Product Safety Commission to mimic the hand contact by children playing in a playground facility constructed with PTW. Three sets of PTW lumber were tested. The first set was used without undergoing any exposure or conditioning, the second set was left in an outdoor environment for natural wreathing and the third set was conditioned with some freeze/thaw cycles. All three sets of samples were subject to wipes by polyester fabric cloth using a CPSC protocol (Thomas *et al*., 2004). After wipes, the cloth samples were extracted with nitric acid for the analysis of copper retained on the cloth during wiping.

The average release of copper after wiping is given in Table 4. The results from the wipe study indicated that MCA and ACA treated wood release approximately the same amount of copper with each wiping.

4. SAWING STUDY

KPC contracted Bureau Veritas North America to conduct a sawing study to simulate personnel exposure to copper from air samples at job site during sawing of PTW. The sawing study was conducted on PTW purchased from retail stores in US. The following PTW was used in the study:

- Southern yellow pine treated with MCA @ 1.0 kg/m^3
- Southern yellow pine treated with MCA @ 2.4 kg/m^3
- Southern yellow pine treated with ACQ-D @ 3.2 kg/m^3
- Canadian pine treated with Copper Azole Type B (CA-B) @ 1.7 kg/m^3

Each PTW board was cut several times within a two to three time frame with an electric circular saw. The personnel who cut the boards worn two air sampling pumps to collect air samples. One sampling pump equipped with mixed cellulose ester (MCE, pore size 0.8 µm) filters used an air flow rate of 2.0 litres per minute (LPM) to collect air samples for determination of total copper, and the second sampling pump with 25mm diameter MCE (pore size 0.45 µm) used an air flow rate of 10 LPM to collect air samples to be analysed by transmission electron microscopy (TEM) equipped with energy dispersive spectroscopy (EDS) and an SBIG digital imaging system. In addition to this sampling pump pairs, areas within the close proximity of the cut were also equipped with pairs of sampling pumps at the same height as the wood (approximately waist height) to collect air samples. One pair was collected at approximately 7 inches away, another pair approximately 18 inches away, and a third pair approximately 32 inches away from the cut. Area sampling pumps continued to collect air samples for approximately 240 minutes after the cut. Each PTW board was cut in a closed room that remained closed for the duration of each sampling event.

The samples collected in the first air pump for determination of total copper were analysed by ICP following The National Institute for Occupational Safety and Health (NIOSH) 7300 protocol. The air samples collected in the second air pump were analysed by TEM-EDS. The ICP analysis was conducted by an American Industrial Hygiene Association (AIHA) accredited lab located in Novi, Michigan. The TEM-EDS study was conducted at an AIHA accredited lab located in Kennesaw, GA.

The ICP result of total copper is given in Table 5. The MCA @2.4 kg/m^3 sample showed trace amount of copper present at 7" vicinity collecting area, while all other samples showed negligible amount of copper (all below detection limit).

The TEM micrographs of air samples collected are shown in Figures 8a – 11a, and the corresponding EDS spectra for copper are as Figure 8b – 11b. Majority of the particles with dark contrast colour were found embedded in wood matrix, and the particles showing dark colour were confirmed by EDS as copper particles. Very occasionally, free copper particles that were not embedded in wood matrix were also found as shown in Figures 12a – 15a, and the identify of copper is confirmed by EDS as shown in Figures 12b – 15b.

5. CONCLUSIONS

The water leaching studies indicated that micronized copper treated wood has substantially less copper leached than its soluble counterpart, resulting in a much lower potential impact on the environment. For the micronized copper treated wood, greater than 95% copper leached from PTW is in ionic form. Only small amount of copper leached is in particulate form. The results from wipe test indicate that both MCA and its soluble counterpart CA released approximately the same amount of copper with each contact. The sawing study indicated that the copper release from all PTW during sawing at job site is negligible. Majority of copper particles in the collected air samples during sawing were embedded in wood matrix, and only occasional free copper particles were found.

6. REFERENCES

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Table 1. The total copper leached from SPLP Water Leaching Solution (EPA, 2014)

Wood Size & Preservatives	Copper Measured in the Unfiltered Fraction After Leaching in mg or (mg/m²)			
	Wood Block		Sawdust	
	24 hours	72 hours	24 hours	72 hours
MCA-1	7.9 ± 0.8 (162 ± 16)	11.1 ± 0.5 (251 ± 8)	3.5 ± 0.7 (0.35 ± 0.07)	6.5 ± 2.3 (0.64 ± 0.22)
MCA-2	5.5 ± 1.5 (99 ± 30)	7.6 ± 3.0 (151 ± 55)	4.3 ± 0.3 (0.43 ± 0.02)	8.5 + 3.1 (0.83 ± 0.31)
ACA	30.3 ± 9.0 (571 ± 237)	65.6 ± 3.0 (1246 ± 39)	12.5 ± 2.1 (1.23 ± 0.20)	9.6 + 0.5 (0.96 ± 0.05)

Table 2. Mass Balance of Copper Released from Wood Blocks during Leaching(EPA, 2014)

Duration (Hour)	Leaching Solution	Total Cu Released (mg)	Ionic Released		Particulate Released		Filtration Recovery, %
			mg	%	mg	%	
	MCA-1						
24	NaCl	0.90	0.86	95	0.04	4.8	100
	NaNO3	0.67	0.74	110	0.02	3.6	113
	SPLP	0.79	0.71	89	0.05	6.3	96
72	NaCl	1.08	1.06	98	0.02	1.6	100
	NaNO3	1.08	0.99	92	0.04	4.1	96
	SPLP	1.11	1.06	96	0.07	6.3	102
	MCA-2						
24	NaCl	0.49	0.47	95	0.02	4.9	100
	NaNO3	0.57	0.51	89	0.02	3.6	93
	SPLP	0.55	0.52	95	0.03	5.2	100
72	NaCl	1.00	0.95	94	0.03	2.9	97
	NaNO3	0.71	0.63	89	0.03	4.5	93
	SPLP	0.76	0.67	89	0.05	6.0	95
	ACA						
24	NaCl	4.81	4.66	97	0.06	1.2	98
	NaNO3	2.76	2.66	96	0.03	1.2	98
	SPLP	3.03	2.90	96	0.07	2.4	98
72	NaCl	5.92	6.07	103	0.08	1.3	104
	NaNO3	5.22	4.34	83	0.09	1.7	85
	SPLP	6.56	6.95	106	0.12	1.8	108

Table 3. Particulate Copper Released and Fraction with Each Filter Size (EPA, 2014)

Mixing Duration	Leaching Solution	Total Particulate Cu		% Particulate Cu @ Filter Size		
		mg	%	>2.5 µm	0.45 – 2.5 µm	10 kDa – 0.45 µm
	MCA-1					
24 hours	NaCl	0.04	4.8	3.9	0.8	0.1
	NaNO3	0.02	3.6	2.9	0.5	0.2
	SPLP	0.05	6.3	5.2	1.0	0.1
72 hours	NaCl	0.02	1.6	0.9	0.6	0.1
	NaNO3	0.04	4.1	3.4	0.6	0.2
	SPLP	0.07	6.3	5.4	0.7	0.1
	MCA-2					
24 hours	NaCl	0.02	4.9	4.1	0.7	0.1
	NaNO3	0.02	3.6	2.7	0.8	0.1
	SPLP	0.03	5.2	4.1	1.0	0.1
72 hours	NaCl	0.03	2.9	2.1	0.7	0.1
	NaNO3	0.03	4.5	3.7	0.6	0.2
	SPLP	0.05	6.0	5.1	0.8	0.1
	ACA					
24 hours	NaCl	0.06	1.2	0.8	0.3	0.1
	NaNO3	0.03	1.2	0.8	0.3	0.1
	SPLP	0.07	2.4	1.9	0.4	0.1
72 hours	NaCl	0.08	1.3	0.9	0.3	0.1
	NaNO3	0.09	1.7	1.3	0.3	0.1
	SPLP	0.12	1.8	1.4	0.4	0.1

Table 4. Average Release of Copper during Wiping Study (EPA, 2014)

Weathering/ Conditioning	Copper Released with Different Preservatives (mg/m^2)			Periods
	MCA-1	MCA-2	ACA	
Outdoor	1.4 ± 0.8	1.4 ± 0.6	1.4 ± 0.7	Days 34 - 399
Freeze/Thaw	0.8 ± 0.6	0.3 ± 0.1	0.2 ± 0.1	Cycles 12 - 24
No Weathering	1.6 ± 0.5	0.8 ± 0.1	0.3 ± 0.1	Samplings 3 - 12

Table 5. The Total Copper in the Air Samples by ICP

PTW	Personal		7" Away		18" Away		32" Away	
	µg	mg/m^3	µg	mg/m^3	µg	mg/m^3	µg	mg/m^3
MCA @ 1.0 kg/m^3	< 1	< 0.23	< 1	<0.0004	< 1	< 0.0004	< 1	< 0.0004
MCA @ 2.4 kg/m^3	< 1	< 0.23	1.5	<0.0006	< 1	< 0.0004	< 1	< 0.0004
ACQ-D @ 3.2 kg/m^3	< 1	< 0.22	< 1	<0.0004	< 1	< 0.0004	< 1	< 0.0004
CA-B @ 1.7 kg/m^3	< 1	< 0.22	< 1	<0.0004	< 1	< 0.0004	< 1	< 0.0004

Figure 1. Copper Level in the Leachates with AWPA E11 Water Leaching

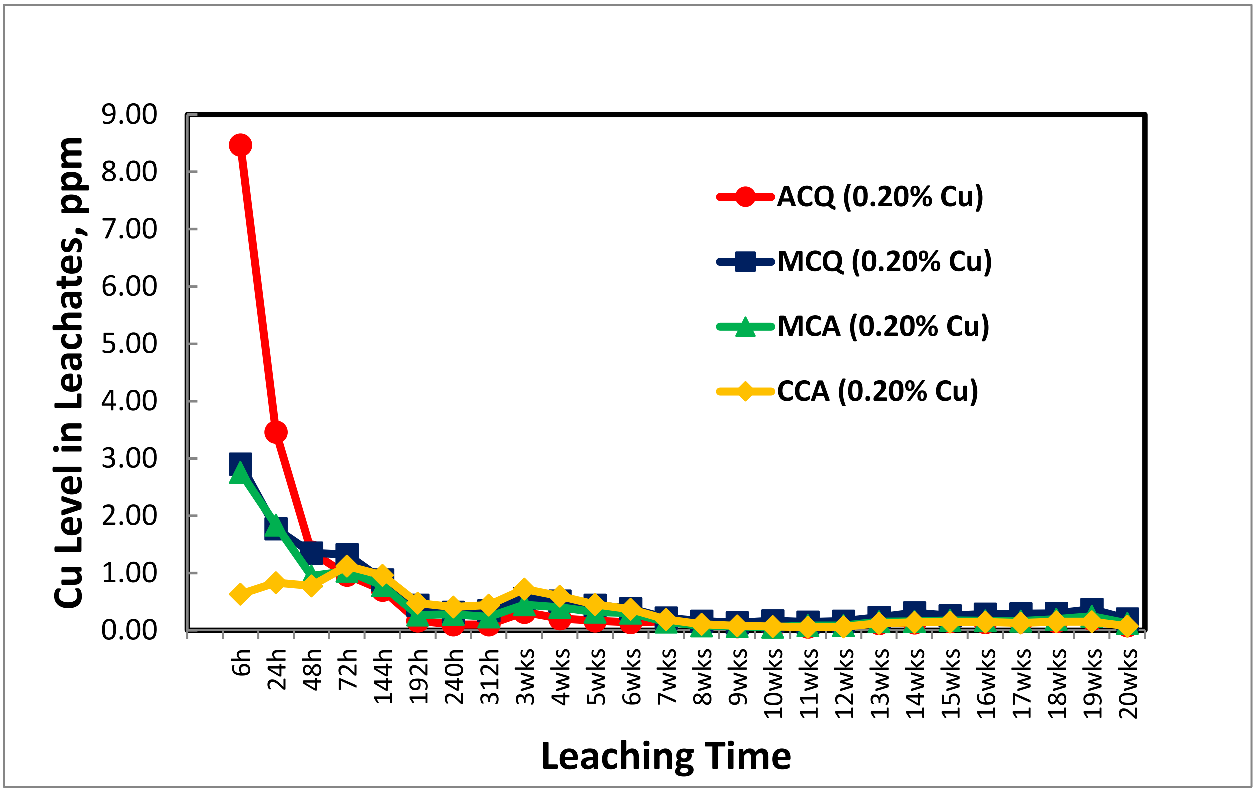


Figure 2. Comparison of ACQ-D Copper Leaching from Acidified and Non-Acidified Leachates

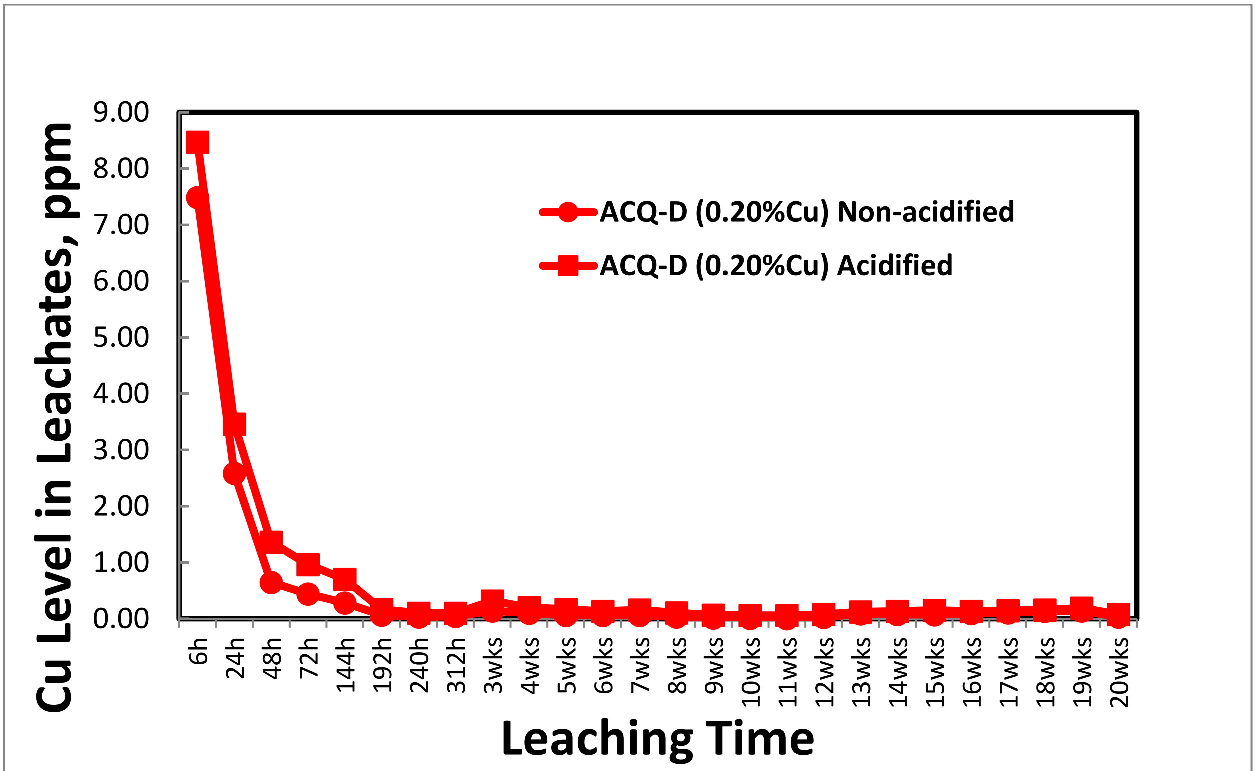


Figure 3. Comparison of MCQ Copper Leaching from Acidified and Non-Acidified Leachates

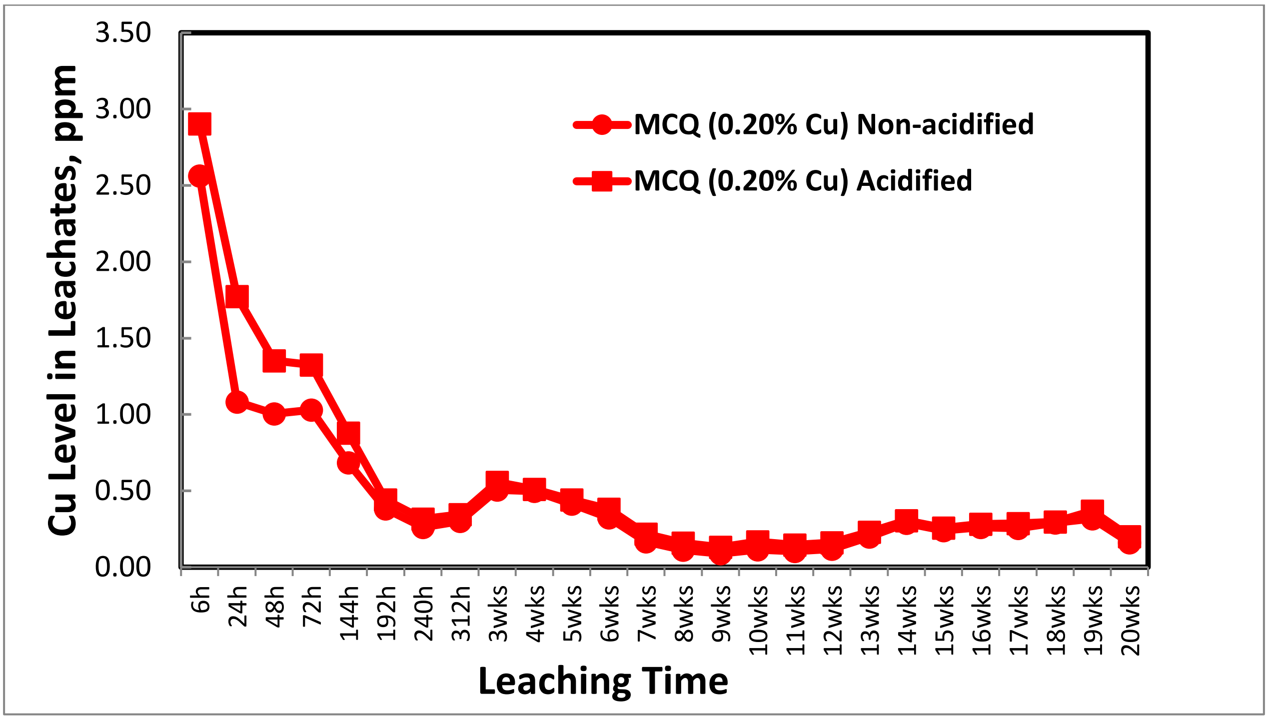


Figure 4. Comparison of MCA Copper Leaching from Acidified and Non-Acidified Leachates

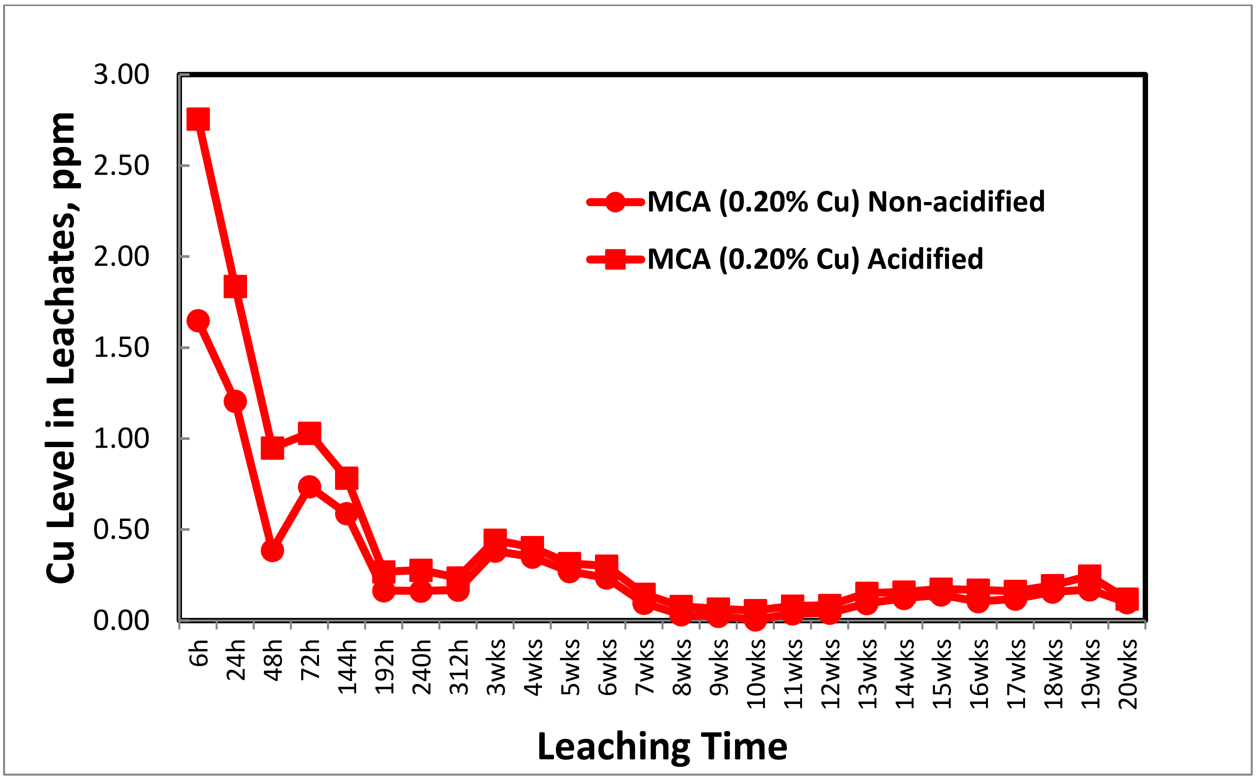


Figure 5. Copper Leaching from Wood after 14-days AWPA E11 Leaching Period

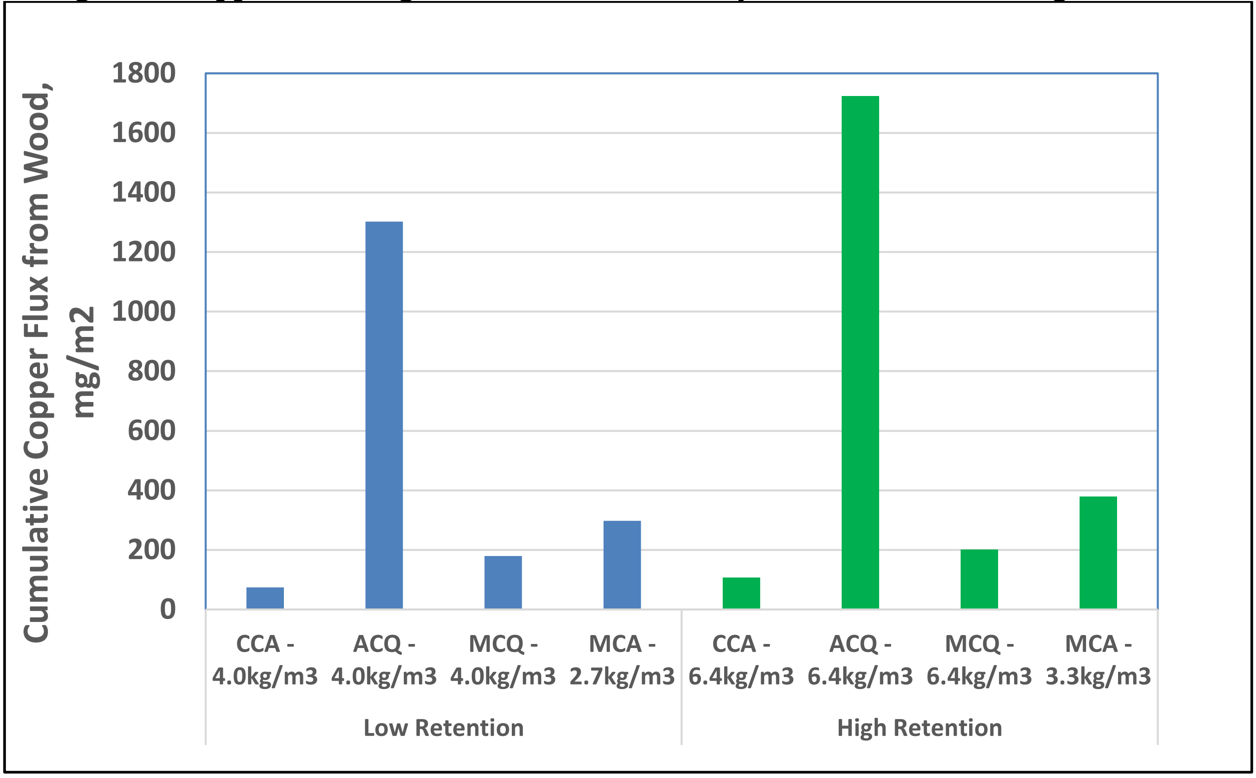


Figure 6. Copper Leaching from Wood after OECD Leaching Period

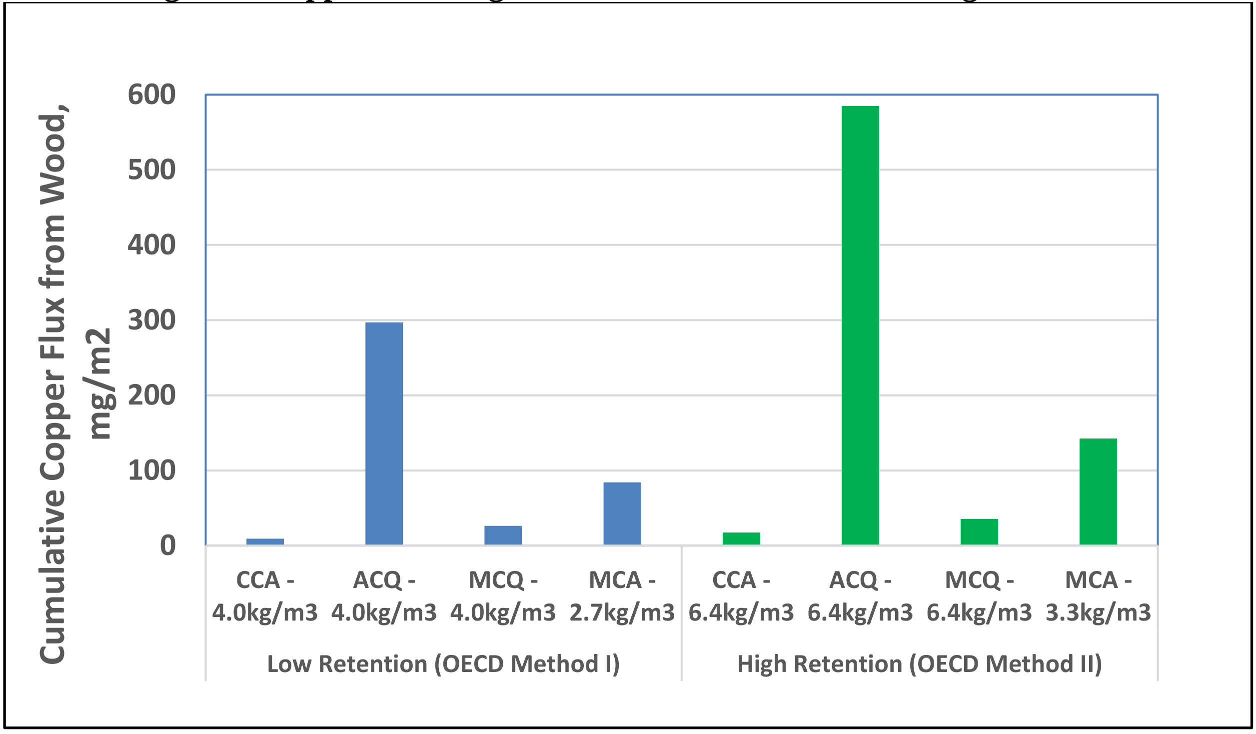


Figure 7. Copper Leaching from Full Dimension Wood after Spray or Immersion Period

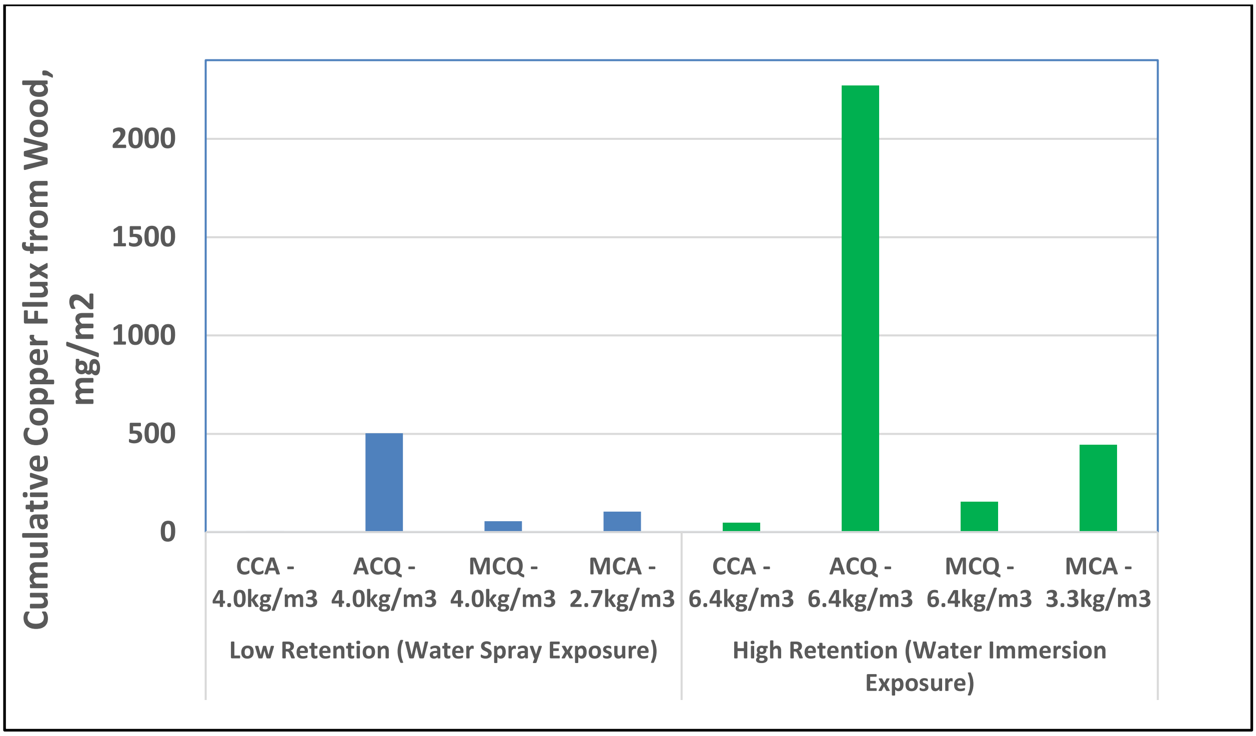


Figure 8. TEM Micrograph and EDS Spectrum of the Sample Collected from MCA @1.0kg/m^3 Treated Wood

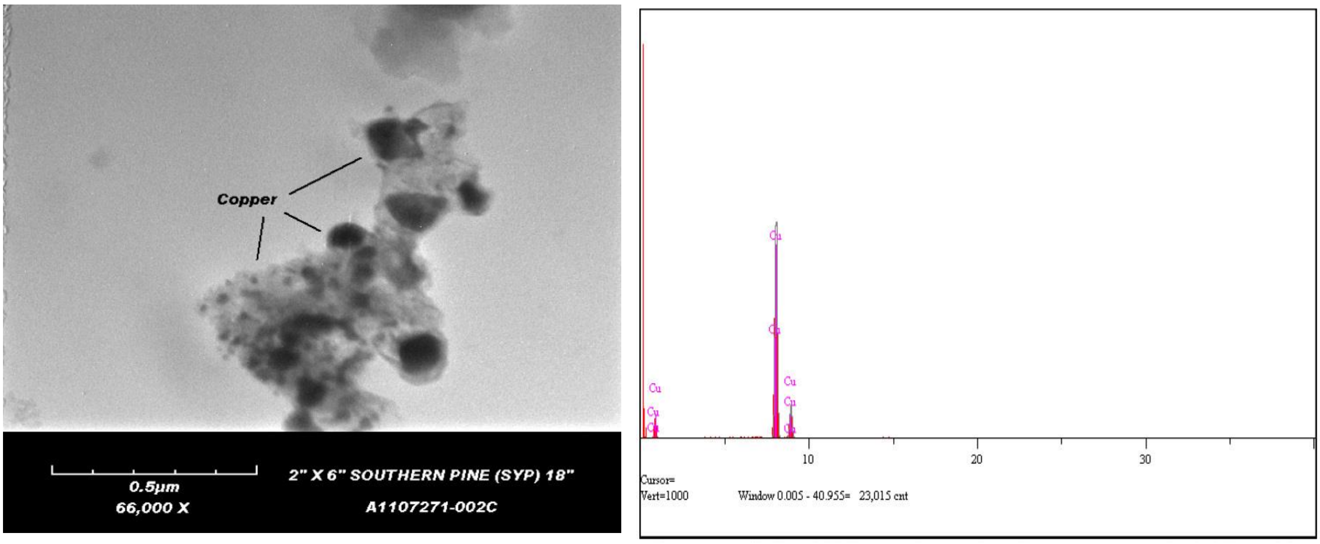
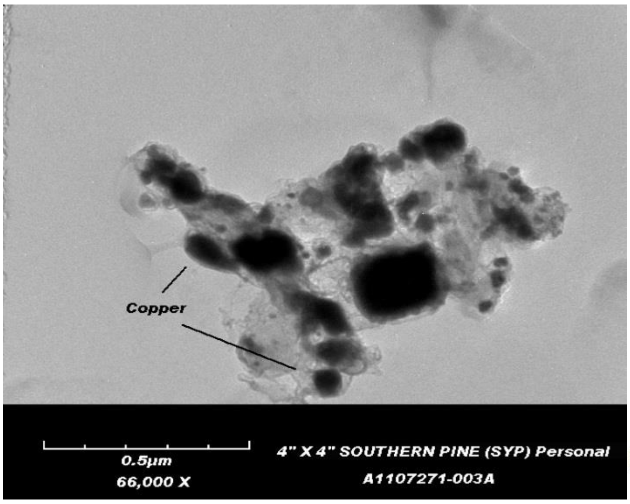
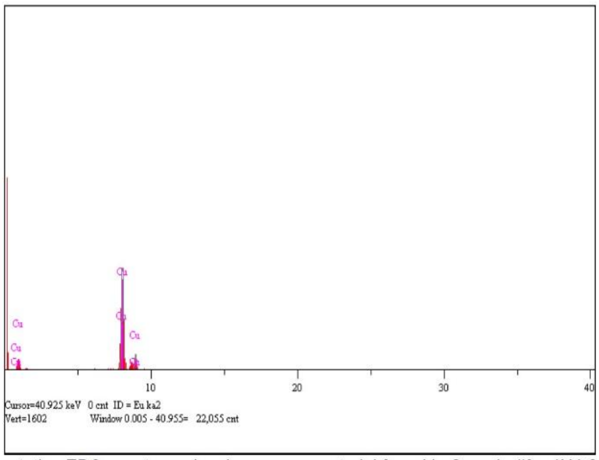


Figure 9. TEM Micrograph and EDS Spectrum of the Sample Collected from MCA @1.0kg/m^3 Treated Wood





Representative EDS spectrum showing copper material found in Sample #3 - 4X4 Southern Pine (SYP) personal.

Figure 10. TEM Micrograph and EDS Spectrum of the Sample Collected from ACQ-D @3.2 kg/m³ Treated Wood

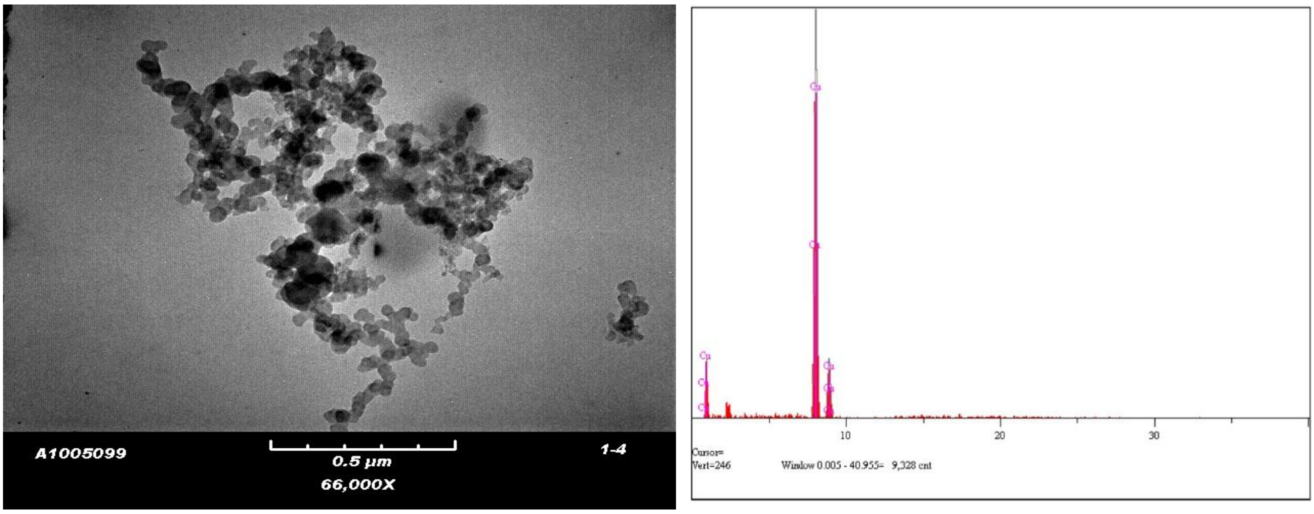


Figure 11. TEM Micrograph and EDS Spectrum of the Sample Collected from CA-B @1.7 kg/m³ Treated Wood

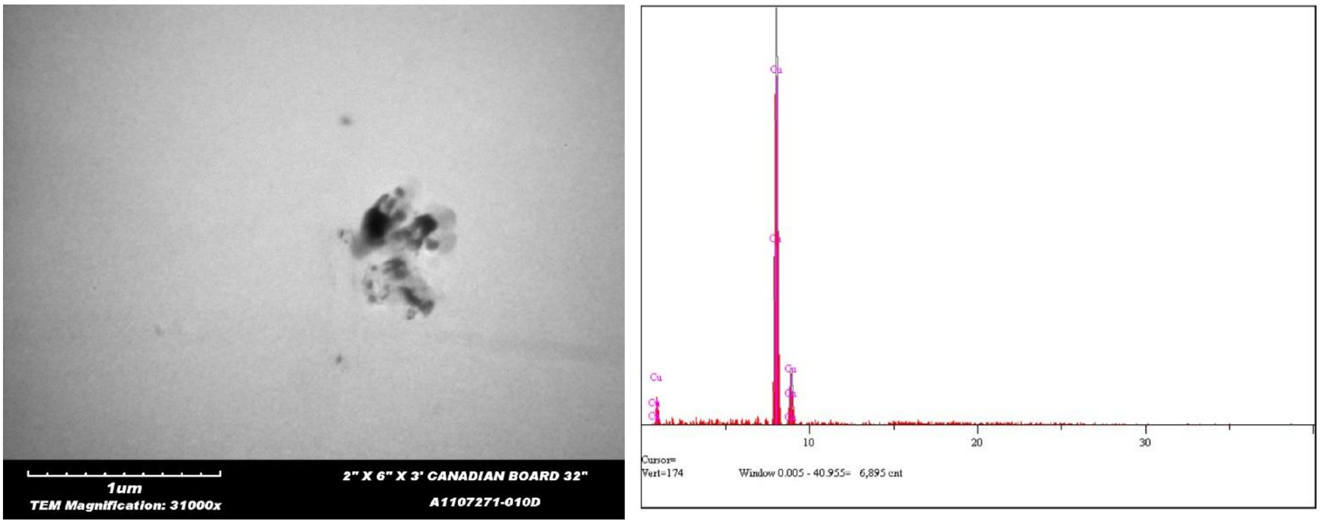


Figure 12. TEM Micrograph and EDS Spectrum Showing Free Copper Particles from MCA @1.0kg/m^3 Treated Wood

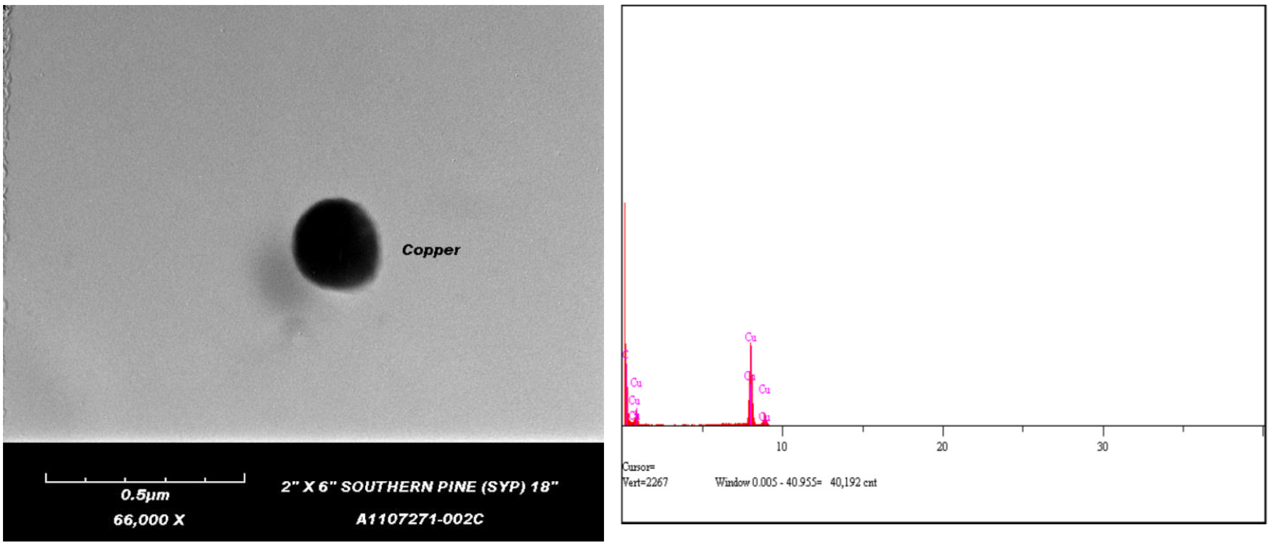


Figure 13. TEM Micrograph and EDS Spectrum Showing Free Copper Particles from MCA @2.4 kg/m^3 Treated Wood

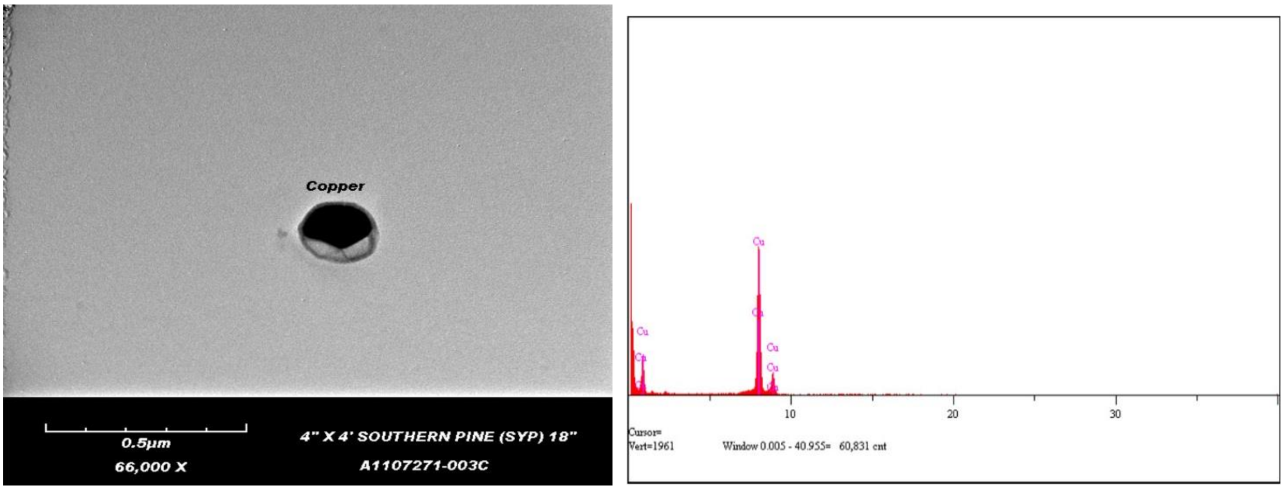


Figure 14. TEM Micrograph and EDS Spectrum Showing Free Copper Particles from ACQ-D @3.2 kg/m^3 kg/m^3 Treated Wood

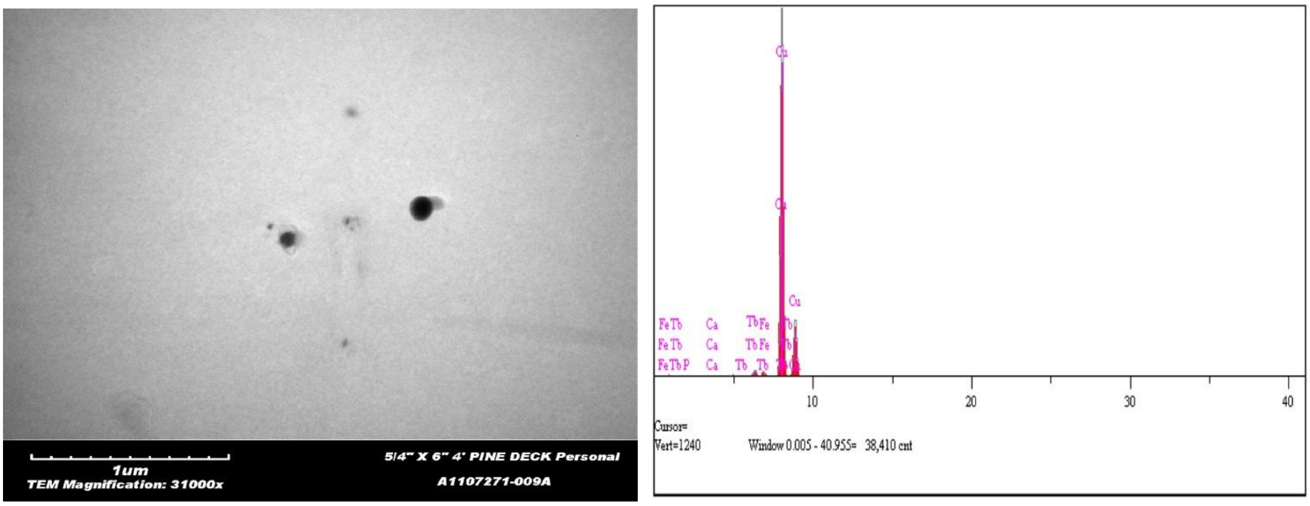
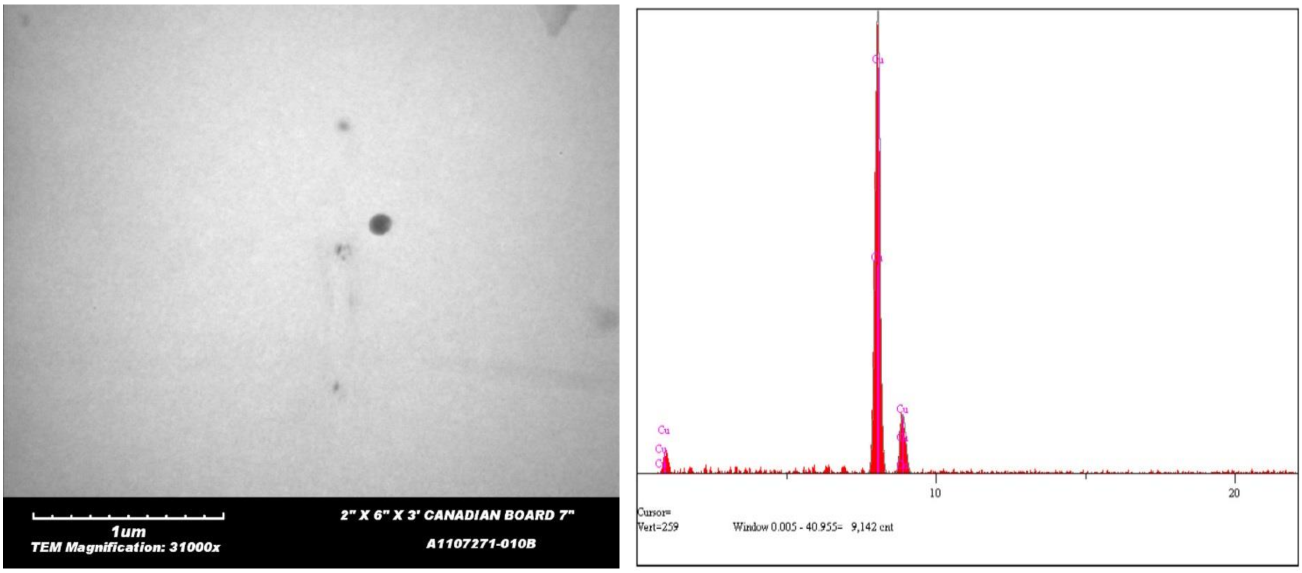


Figure 15. TEM Micrograph and EDS Spectrum Showing Free Copper Particles from CA-B @1.7 kg/m^3 Treated Wood



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DESIGNING SAFE AND DURABLE WOOD DECKS AND BALCONIES

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Abstract

While wood decks and balconies can be robust and long-lasting structures, they can be challenging to design and construct, primarily because of their exposure to the elements. Adherence to a set of design principals is necessary to ensure that these structures meet their intended lifespans and do not result in harm to building occupants. Post construction forensic investigations indicate that key durability criteria and code requirements are often not considered leading to premature failures and unforeseen costs placed on building owners. A lack of best practices education material directed at the residential construction market was identified as an important barrier to durable and safe wood deck and balcony construction that needed to be addressed.

In order to encourage better design and construction of these exterior wood structures, BC Housing commissioned RDH Building Science Inc. to produce a guidance document that highlighted the salient design considerations for residential builders. The *Illustrated Guide for Building Safe and Durable Wood Decks and Balconies* covers the design, construction, and maintenance of wood deck and balcony structures. The guide summarizes common performance issues facing these structures and discusses important moisture design principals that should be applied. Common structural design parameters largely originating in the BC Building Code are also discussed. The following paragraphs describe the common design features of safe and durable wood decks and balconies.

Wood deck durability is improved by preventing or reducing exposure to the natural elements. Where possible wood decks and balconies should be isolated from moisture point sources such as gutters, planters, and dryer ducts. Where exposure is inevitable, design measures such as deck sloping and drains can be utilized to move bulk water away from critical interfaces and details. Furthermore, strategies that promote ventilation should be considered to allow for drying of wetted wood components. Proper detailing of key interfaces such as the deck edge and building enclosure attachment are also covered.

The compatibility and resilience of metal elements and wood materials utilized in deck and balcony construction play an important role in their respective lifespans. All wood materials should be decay resistant as they are exposed to rain and other moisture sources. Pressure preservative treatments are typically needed; however, some naturally durable wood species such as cedar can be used effectively for certain deck components. Fasteners and flashings must be selected that do nor rust when exposed to corrosive wood preservatives. Typically, stainless steel and hot-dipped galvanized treatments provide adequate protection in this context.

Once constructed, all wood decks and balconies require regular maintenance as dirt and debris can limit drainage of the deck surface leading to water ponding and subsequent damage. Furthermore, important safety components such as guard rails should be inspected on a regular basis and repaired as necessary. These steps can significantly increase the service life before significant renewals are necessary. Wood decks and balconies must also be designed and constructed to facilitate the eventual replacement of key components such as the waterproof membrane by eliminating the need for unnecessary dismantling or destruction of adjacent components.

Taken together, good design principals can dramatically improve the longevity and safety of these exterior wood structures. The *Illustrated Guide for Building Safe and Durable Wood Decks and Balconies* highlights the most important design, construction, and maintenance considerations for wood decks and balconies with the intent of educating the residential construction market. Future wood deck and balcony structures can expect improved durability and safety outcomes if design principals described in the guide document are carefully applied.

Acknowledgements

The *Illustrated Guide for Building Safe and Durable Wood Decks and Balconies* was developed through extensive consultation with many individuals and organizations involved in the residential construction industry in British Columbia. Specials thanks to Ralph Moore (Aviva Canada) and Paul Morris (FP Innovations) for their important contributions to this document. This document would not have been possible without the support of BC Housing and in particular Denisa Ionescu.

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IMPROVING THE PERFORMANCE OF CLEAR COATINGS ON WOOD THROUGH THE AGGREGATION OF MARGINAL GAINS

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Summary

Remarkable increases in the performance of complex systems can be achieved by a collective approach to optimizing individual factors that influence performance. This approach, termed the aggregation of marginal gains, is tested here as a means of improving the performance of exterior clear-coatings. We focused on five factors that influence clear-coating performance: dimensional stability of wood; photostability of the wood surface; moisture ingress via end-grain; coating flexibility and photostability; and finally coating thickness. We performed preliminary research to select effective wood pre-treatments and durable clear-coatings, and then tested coating systems with good solutions to each of the aforementioned issues (factors). Red oak and radiata pine panels were modified with PF-resin, end-sealed, and thick acrylic, alkyd or spar varnishes were applied to the panels. Panels were exposed to the weather and the level of coating defects was assessed every year over a 4-year period. All of the coatings are performing well on PF-modified pine after 4 years' outdoor exposure. In contrast, coatings failed after 2 years on unmodified pine and they are failing on PF-modified oak. We conclude that our approach shows promise. Future research will build on the current work by developing solutions to additional factors that influence clear-coating performance.

Full paper freely available on-line at: http://www.mdpi.com/2079-6412/6/4/66