TREATMENTS TO IMPROVE THE DIMENSIONAL STABILITY OF WHITE SPRUCE CLADDING

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Abstract. Most wood cladding, in North America, is coated with paint or stain. Key performance parameters include durability, dimensional stability of the wood, and adhesion and color stability of the coating. Changes in wood MC below the FSP result in dimensional changes. This creates stresses in the wood which may manifest as checks and cracks. These impact the appearance of wood products and limit the use of wood in some applications. Many chemical treatments to improve wood stability have been developed, though they are generally only applied to wood species with high permeability. The present work investigates several commercial-scale and lab-scale modification treatments for their ability to stabilize white spruce, a refractory softwood species typically produced as boards containing both sapwood and heartwood for cladding applications. Modified white spruce was evaluated for weight percent gain after treatment, dimensional stability in humidity and immersion, total color change after accelerated UV exposure, and coating adhesion before and after UV exposure. All treatments improved stability with antiswelling efficiency between 11 and 59%. However, these treatments were also associated with increased color change after accelerated UV exposure and poorer adhesion of an acrylic water-based stain. The improvements in dimensional stability were generally lower than those reported for permeable species, and it is unclear if they would meet end-user expectations for cladding performance. Additional research is needed to further enhance performance and overcome the resulting photostability and coating adhesion challenges.

Keywords: Cladding, dimensional stability, spruce, wood modification.

INTRODUCTION

Dimensional stability is particularly important in exterior applications, such as cladding and decking, where wood is exposed to large and rapid changes in MC, and for which checking and cracking negatively impact the esthetic value of the wood. In eastern Canada, white spruce (*Picea glauca* (Moench) Voss) is commonly used for exterior cladding applications. Refractory softwoods are the most abundant wood products in Canada and make up a significant proportion of the fiber available in many parts of the world. Many of these species, including most *Abies* and *Picea* species, have heartwood with low natural durability (Scheffer and Morrell 1998). These wood species are less competitive in certain exterior above-ground applications such as cladding,

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due to their low natural durability and stability, and the difficulty of applying preservatives or chemical modification treatments. Anatomically, spruce differs from pine by its pit structure and by the diameter of its resin canals. Indeed, the piceoid pits found in spruces are a lot smaller than the pinoid pits of yellow pines (Wheat et al 1996), and the diameter of the resin canals of spruces are also a lot smaller than those of pines (Panshin and de Zeeuw 1980). In addition, the epithelial cells located inside the longitudinal and transverse resin canals of pines have thin walls (possibly nonlignified), whereas those of spruce have thick walls (more lignified). Together, these factors explain why liquid diffusion is more difficult in refractory species compared with permeable ones.

Wood stability is influenced by physical, ultrastructural, and chemical factors that affect wood–water relationships (Hillis 1984). Wood has a dynamic and complex relationship with water, continually absorbing and desorbing water as environmental conditions change. Moisture gain associated with exposure to liquid water or water vapor results in swelling until the FSP is reached. Similarly, wood shrinks as it dries below the FSP. This fundamental behavior limits the applications where wood can be used and impacts performance (Sargent 2019). This dimensional instability must be considered in applications where wood may be exposed to liquid water or significant changes in humidity. Fluctuating MC creates stresses in the wood that can result in checks and cracks. These checks and cracks affect the appearance of wood and can also lead to changes in mechanical properties. Wood that is naturally more stable, or treated to be more stable, may have a more natural uniform appearance valued by end users (Høibø and Nyrud 2010).

Treatments to improve the dimensional stability of wood have been studied for many years (Tarmian et al 2020). Physical approaches, such as kerfing or incising, do not alter the stability of the wood material but they can relieve moisture-induced stresses that lead to checking and cracking. These approaches have been shown to work on railway ties (Brentlinger 1960) and deck boards (Cheng and Evans 2018), but they are not applicable to all products.

Thermal modifications have been extensively studied for their ability to improve wood material properties (Stamm and Hansen 1937; Hill et al 2021). Improved dimensional stability is consistently reported for several different modification processes and species (Esteves and Pereira 2008; Militz and Altgen 2014; Sandberg and Kutnar 2016). This improvement is caused by chemical reactions in hemicellulose and lignin that result in increased crosslinking (Tjeerdsma et al 1998). One of the advantages of thermal modification is that it is not dependent on chemicals moving into the wood. This enables the stabilization of larger dimension pieces of refractory wood species (Zelinka et al 2022). Researchers have also explored chemical treatments to catalyze the thermal degradation reactions and enable them to occur at lower temperatures (Qu et al 2021; Wang et al 2022). Pretreatments with different aluminum solutions before thermal treatment were shown to significantly improve the dimensional stability of Chinese fir (*Cunninghamia lanceolata* (Lamb.) Hook) and Chinese white poplar (*Populus* × *tomentosa* Carrière) wood at relatively low temperatures (130-160°C). The stability achieved was similar or better than the dimensional stability achieved with only thermal treatment under high temperatures. Nevertheless, such pretreatments require penetration into the wood and may not be as effective on refractory species.

Water-repellent coatings or surface treatments that enhance hydrophobicity can improve dimensional stability by reducing the uptake of liquid water or atmospheric moisture. However, this is a potentially risky approach as any damage to the coating will expose wood that is susceptible to moisture and movement. Some coatings may also inhibit the drying of wood once it gets wet, which can create conditions that increase the risk of decay (Norton and Francis 2008; Schauwecker et al 2010).

Cell wall bulking treatments have been explored to stabilize wood. Rowell (1988) describes three types of chemical bulking treatments: nonbonded and leachable, nonbonded and nonleachable, and bonded and nonleachable. Sugars, salts, and polyethylene glycol (PEG) are nonbonded and leachable. PEG has been extensively studied for its ability to stabilize wood (Stamm 1959; Schneider 1969) but has limited applications due to its leachability and hygroscopicity. Nonbonded and nonleachable treatments include treatments that form polymers in the wood, such as phenol-formaldehyde (Furuno et al 2004). Bonded and nonleachable treatments include chemical reactions with the cell wall. These include well-known chemical modification techniques, such as acetylation and furfurylation (FUR).

Acetylation results from the reaction of acetic anhydride with the hydroxyl groups in wood. The acetyl groups are less hygroscopic and leave the wood in a permanently swollen state. This reduces the ability of wood to absorb water. A 20% acetyl content has been reported to reduce shrinkage by about 70% (Stamm and Tarkow 1947). Acetylation of spruce has been reported, though test materials were limited to 1/8 in. (3.2 mm) thick (Tarkow et al 1955). Baird (1969) found vapor phase treatments with acetic anhydride and butyl isocyanate that could modify and stabilize wood, though it was noted that these would likely only be effective on thin materials.

Treatment of wood with furfuryl alcohol resin, catalysts, and heat has been reported to stabilize and enhance the properties of several wood species (Stamm 1977; Schneider 1995). The properties of furfurylated wood depend on the uptake and reaction of the furfuryl alcohol polymer with the wood cell wall. At high modification levels there is increased dimensional stability, mechanical properties, and resistance to biodegradation (Lande et al 2004). Detailed studies on the reactions between furfuryl alcohol polymer and the wood cell wall found evidence of condensation reactions between uncrowded ring positions and lignin side chains (Shen et al 2021).

Wood modification with dimethyloldihydroxyethyleneurea (DMDHEU) has been used to enhance wood properties, including dimensional stability (Militz 1993; Emmerich et al 2019). Research on DMDHEU treatments has focused on relatively permeable species (Militz and Norton 2013; Derham et al 2017).

Several organosilane treatments have been applied to permeable species (Schneider and Brebner 1985; Sèbe and Jéso 2000; Mai and Militz 2004). These treatments are associated with improved antishrink efficiency, lower moisture uptake, and increased durability (Donath et al 2004). Research into the mode of action has found that organosilanes influence the rate of moisture uptake, but do not reduce the maximum swelling (De Vetter et al 2010). This explains some of their poor results in laboratory decay tests yet good performance in field tests where moisture conditions are variable (De Vetter et al 2009). Improvements in the dimensional stability of white spruce impregnated and reacted with organosilanes have been reported (Schorr and Blanchet 2020).

More recently, wood modification with citric acid and sorbitol has been shown to improve dimensional stability and biological resistance (Larnøy et al 2018; Mubarok et al 2020). Lower EMC has been associated with covalent bonding and cross-linking of the polyesters with wood polymer constituents (Kurkowiak et al 2021). High molecular weight sorbitol-citric acid polyesters in the wood result in cell wall bulking (Kurkowiak et al 2023). Studies on wood modification with citric acid and sorbitol have been largely limited to permeable species such as pine (*Pinus sylvestris* L.) and beech (*Fagus sylvatica* L.) (Beck 2020; Mubarok et al 2020).

Chemical modification methods for enhancing the dimensional stability of wood have been extensively reviewed (Mai and Militz 2004; Rowell 2006; Kocaefe et al 2015; Gérardin 2016; Sandberg et al 2017; Sargent 2019). Most stabilization treatments, particularly those involving chemical impregnation, have focused on permeable woods or very thin specimens. It is unclear to what extent refractory wood species' anatomy affects the capacity of chemical treatment to improve dimensional stability.

This paper reports on selected modifications of white spruce lumber. White spruce is a North American softwood that generally has a thin band (approximately 3 cm, Quiñonez-Piñón and Valeo 2017) of relatively permeable sapwood surrounding larger volumes of refractory heartwood. Thin white spruce boards (>25 mm) milled for cladding or decking applications are often cut from the outer parts of the log and contain a mixture of sapwood and heartwood. This can manifest as sapwood corners, a sapwood edge, or a sapwood face depending on the cutting pattern employed. It is generally not feasible to cut pure sapwood boards from white spruce due to the relatively low volumes of sapwood present. The present work evaluated the dimensional stability and coating performance of commercially milled mixed sapwood-heartwood white spruce boards, modified with a series of commercial-scale and lab-scale treatments.

MATERIALS AND METHODS

Kiln-dried boards from a mix of heartwood and sapwood of white spruce (*Picea glauca* (Moench) Voss) without any knots or defects from Bois d'oeuvre Cedrico (Quebec, Canada) were used for this study.

Commercial Treatments

For all these commercial treatments, the processes are proprietary and some information cannot be disclosed.

Furfurylation treatment. FUR treatment parameters were described by Boivin and Schorr (2022). Ten white spruce boards (5.9 mm × 127 mm × 1219 mm) were treated by FUR using a commercial process. This process used furfuryl alcohol, which is manufactured industrially by catalytic reduction of furfural. It included a wood impregnation step with furfuryl alcohol and catalysts, followed by a curing step where the furfuryl alcohol was polymerized within the wood cell walls. The treatment is a vacuum pressure process and a heating treatment.

Citric acid: sorbitol treatment. Treatment parameters were described by Schorr et al (2024). Ten white spruce boards (19 mm × 152 mm × 1200 mm) were vacuum-treated for 1 h at 40 mb and then pressure-treated for 2 h at 8 bars with an aqueous citric acid and sorbitol solution in a pilot plant in Norway. Heat treatment at 140°C for 12 h was then initiated.

Thermal modification. The thermal modification was performed by a commercial producer in Quebec, Canada on five white spruce boards (25.6 mm × 152 mm × 2438 mm) in a closed system (atmospheric pressure and oxygen-free) with a maximum temperature of 220°C. After modification, the wood was steam conditioned to a final MC between 3 and 7%.

Laboratory Treatments

Organosilanes and metal treatments. Four laboratory treatments were evaluated in this work. These included an organosilanes treatment (SiTT) and organosilanes treatment followed by impregnation with aluminum (SiTT + Al), as the literature suggests that inorganic solutions, in particular aluminum solutions, can be used as thermal catalysts (Ximenes and Evans 2006; Qu et al 2021; Wang et al 2022). Two inorganic treatments were also evaluated without organosilanes treatment: aluminum treatment alone (Al) and magnesium treatment alone (Mg). Methyltrimethoxysilane (MTMS) (>98%) and hexadecyltrimethoxysilane (HDTMS) (95%) were provided by Gelest, Inc. (Morrisville, PA) and glacial acetic acid (>99%), ethyl alcohol, and aluminum sulfate ($Al_2(SO_4)_3$) (>97%) were provided by Sigma-Aldrich (Toronto, Canada) and magnesium chloride ($MgCl_2$) (>99%) by Laboratoire MAT (Quebec, Canada). The organosilanes solution was prepared by mixing MTMS, ethyl alcohol, glacial acetic acid, and HDTMS in a 1:3.9:0.05:0.33 mass ratio, respectively. First MTMS was mixed with ethanol, then, glacial acetic acid was slowly added to the solution, which was stirred at 60°C for 30 min. Finally, HDTMS was added, and the solution was stirred for 60 min. Treatment parameters are described by Schorr et al (2022).

Inorganic treatment alone with aluminum or magnesium cycle impregnation was also evaluated on white spruce wood to assess the possibility of using these inorganic treatments along with mild temperature thermal treatment instead of higher temperature thermal treatment. For the aqueous inorganic treatment, the solution was prepared with $Al_2(SO_4)_3$ or $MgCl_2$ in distilled water. The concentration of the $Al_2(SO_4)_3$ was 0.44 M. The concentration of the $MgCl_2$ solution was 1.57 M.

Fifteen white spruce boards of 19 mm × 88.9 mm × 254 mm were subjected, for each laboratory treatment, to a 20-min vacuum and then 2 h pressure treatment cycle with organosilanes solutions and/or aluminum or magnesium solutions (see sequence in Table 1). After 24 h at ambient temperature, all treated samples were heat treated at 120°C for 24 h.

Weight Percent Gain

All boards before and after treatment were conditioned at 20°C and 50% RH. The weight of the boards before and after treatment was measured, and weight percent gain (WPG) was calculated using the following equation:

$$\mathrm{WPG} = \frac{\boldsymbol{W_1} - \boldsymbol{W_0}}{\boldsymbol{W_0}} \times 100 \tag{1}$$

where W_0 is the weight of the samples before treatment (stabilized in a conditioning room at 20°C and 50% humidity) and W_1 is the weight of the samples after treatment and after stabilization in a conditioning room at 20°C and 50% humidity.

Dimensional Stability

Humidity. Fifteen specimens were taken from the boards of each treatment. For laboratory treatments, one specimen was cut from each board treated. For commercial treatments, two or three specimens were cut from each board (three samples from each thermally treated boards of 2438 mm long and two samples from each chemically treated boards of 1219 mm long). All test specimens (50 mm × 50 mm × 16 mm) were placed in a conditioning chamber at 20°C/50% RH until mass was constant (difference of less than 0.2% after 24 h) and dimensions constant (difference of less than 0.1 mm after 24 h). Once stable, the mass of the samples was recorded, and radial, tangential, and longitudinal dimensions were measured using a caliper. The same specimens were then placed in a conditioning chamber at 20°C/90% RH. When the masses were constant, the radial, tangential, and longitudinal dimensions were measured using a caliper. The samples were then returned to 20°C/50% RH. This cycle was repeated three times.

Dimensional stability was determined by antiswelling efficiency (ASE). A higher ASE indicates greater dimensional stability. ASE is calculated from the swelling coefficients of treated and untreated samples, subjected to different conditions, according to equations taken from DIN 52184 (DIN 1979)

$$\mathrm{Sw_{ctrl}} = \left(\frac{V_{\mathrm{ctrl90}} - V_{\mathrm{ctrl50}}}{V_{\mathrm{ctrl50}}}\right) \times 100 \tag{2}$$

$$\mathrm{Sw_{tr}} = \left(\frac{V_{\mathrm{tr90}} - V_{\mathrm{tr50}}}{V_{\mathrm{tr50}}}\right) \times 100 \tag{3}$$

$$\mathrm{ASE}\ (\%) = \left(\frac{\mathrm{Sw_{ctrl}} - \mathrm{Sw_{tr}}}{\mathrm{Sw_{ctrl}}}\right) \times 100 \tag{4}$$

where V_{ctrl90} is the volume of the sample untreated at 90% RH; V_{ctrl50} is the volume of the sample untreated at 50% RH; V_{tr90} is the volume

Table 1. Details of the different impregnation cycles done with organosilanes, aluminum, or magnesium solution on white spruce wood for each treatment.

Treatments	Cycle with organosilanes	Cycle with aluminum	Cycle with magnesium
SiTT (organosilanes)	✓	—	—
SiTT + Al (organosilanes + aluminum)	✓	✓	—
Al (aluminum)	—	✓	—
Mg (magnesium)	—	—	✓

of the sample treated at 90% RH; and V_{tr50} is the volume of the sample treated at 50% RH.

Immersion. Fifteen specimens were taken from the boards of each treatment. For laboratory treatments, one specimen was cut from each board treated. For commercial treatments, two or three specimens were taken from each board (three specimens from each thermally treated boards of 2438 mm long and two specimens from each chemically treated boards of 1219 mm long). All test specimens (50 mm × 50 mm × 16 mm) were placed in a conditioning chamber at 20°C/50% RH until mass was constant (difference of less than 0.2% after 24 h) and dimensions constant (difference of less than 0.1 mm after 24 h). Once stable, the mass of the samples was recorded, and radial, tangential, and longitudinal dimensions were measured using a caliper. The same samples were then immersed in a distilled water bath at 22°C. When the masses were constant (difference of less than 0.2% of mass after 24 h), the radial, tangential, and longitudinal dimensions were measured using a caliper. The samples were then returned to 20°C/50% RH. The immersion cycle was repeated twice. Dimensional stability was calculated based on initial and final dimensions, compared with those obtained for untreated samples using the same calculations presented above for dimensional stability.

Preparation of Finished Samples

Three treated and untreated samples (76.2 mm × 76.2 mm) were finished with a semitransparent acrylic stain. Two coats of stain were applied in accordance with the manufacturer's recommendations. Specimen surfaces were previously sanded with P80 abrasive paper. For specimens placed in an accelerated UV exposure chamber, the sides and back were sealed with epoxy.

Accelerated UV Exposure

Accelerated UV exposure tests were conducted over a period of 2000 h on three unfinished and three finished specimens (76.2 mm × 76.2 mm) per series (untreated, organosilanes, organosilanes + aluminum treated, furfurylated, and esterified white spruce). The samples were placed in a Q-Sun from Q-Lab (Westlake, OH) according to ASTM G155-21 (ASTM 2021). Cycle 1 was followed based on the parameters listed in Table 2.

Color measurements were taken initially, after 250, 500, 1000, and 2000 h of accelerated UV exposure using a Check3 Spectrophotometer from Datacolor (Lawrenceville, NJ), which was quantified using the CIE L*a*b* color space coordinates (Eq 5). The samples were scanned at the same intervals.

$$\begin{aligned} \Delta L^* &= L_1^* - L_0^* \\ \Delta a^* &= a_1^* - a_0^* \\ \Delta b^* &= b_1^* - b_0^* \end{aligned} \quad (5)$$

The total color change (ΔE*ab) was calculated using the equation as follows:

$$\Delta E_{ab}^* = \left[(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2 \right]^{1/2} \quad (6)$$

Crosshatch Test

Coating adhesion performance was assessed before and after accelerated UV exposure, pursuant to ASTM D3359-2023 method B (ASTM 2023) using a precision knife (X-Acto® knife) and a Gardco Temper II template. Three replicates were performed per series. This test was performed on the finished samples only. The samples were rated (from 0B, no adhesion to 5B, perfect adhesion) based on the classification presented in Table 3. Visibility of the underlying wood structure indicates poor coating adhesion.

RESULTS AND DISCUSSION

Application of Stabilization Technologies to White Spruce

White spruce boards were modified with seven treatments to find which treatment is the most suitable to improve the durability and stability of this refractory species for cladding applications. Some treatments are commercially available, such as thermal modification, FUR, and citric

Table 2. Cycle 1 parameters following standard ASTM G155-21.

Exposure duration (h)	2000
Filter	Daylight
Irradiance W/(m^2 • nm)	0.35
Wavelength (nm)	340
Step 1	102 min light, 50% RH at 63°C (black panel temperature), air chamber temperature at 44°C
Step 2	18 min light, water spray at a rate of 5 s/min. RH and black panel not controlled. Air chamber temperature at 44°C

acid sorbitol esterification (SOR), which are mostly used on permeable species. White spruce boards were also treated, at the lab scale, with different noncommercial treatments; organosilanes (SiTT), a combination of aluminum and organosilanes (SiTTAl), aluminum aqueous solution (Al), magnesium aqueous solution (Mg).

Table 4 presents the WPG after treatment on white spruce. Lab scale treatments all showed a WPG of 15% or lower. Low WPG was expected for all laboratory treatments, as the solution strengths were low. Moreover, treatments were not meant to fill the lumen. The low WPG for the aluminum aqueous solution can be explained by the fact that it is mostly used as a thermal catalyst, so it does not react to the wood (Qu et al 2021). Indeed, in Schorr and Boivin (2023), the leaching test on aluminum-treated wood showed that it was leachable.

Commercial treatments with a vacuum-pressure process (FUR and SOR) show similar WPG of 26 and 25%, respectively. For FUR treatment, studies on permeable species, such as Scots pine, have shown that WPG could vary between 15 and 47% depending on the properties needed (Westin et al 2004). For pine (*Pinus pinaster*), a WPG of 38% was obtained (Esteves et al 2011). For Norway spruce, an average WPG of 63% was observed with FUR treatment, but this is due to the small size of the 14 mm diameter cylindrical samples or $1 \times 40 \times 40$ mm^3 samples used (Thygesen et al 2010). For citric acid SOR treatment, permeable species, such as Scots pine, showed a high WPG of 62%. For another refractory species (Norway spruce, *Picea abies* (L.) H. Karst.), a similar WPG as white spruce was obtained (24%) (Schorr et al 2024). Higher WPG was observed for commercial treatments for white spruce in comparison with one obtained with the laboratory scale treatments. This can be explained by the fact that the commercial treatments are meant to fill the lumens and create cross-linking within the wood, which results in a weight increase. WPG for the thermal modification process was not presented as this is not an impregnation process.

Table 3. Classification of adhesion test results according to ASTM D3359-23 (method B).

Classification	Description
5B	The edges of the cuts are completely smooth; none of the squares of the lattice is detached.
4B	Small flakes of the coating are detached at intersections; less than 5% of the area is affected.
3B	Small flakes of the coating are detached along the edges and at intersections of cuts. The area affected is 5-15% of the lattice.
2B	The coating has flaked along the edges and on parts of the squares. The area affected is 15-35% of the lattice.
1B	The coating has flaked along the edges of cuts in large ribbons and whole squares have detached. The area affected is 35-65% of the lattice.
0B	Flaking and detachment are worse than grade 1.

Table 4. Average weight percent gain (WPG) in white spruce after each treatment.

	Chemical treatment	WPG after treatment (%)[a]
Lab scale treatment	Al (aluminum)	4 (5)
	Mg (magnesium)	15 (4)
	SiTT (organosilanes)	11 (5)
	SiTTAl (organosilanes + aluminum)	12 (6)
Commercial treatment	FUR (furfurylation)	26 (7)
	SOR (esterification)	25 (19)

[a]Standard deviations appear in parentheses.

Dimensional stability. Figure 1 shows the humidity and immersion volumetric dimensional stability (ASE) of white spruce samples treated with each of the lab scale and commercial treatments (FUR, SOR, and thermal modification). Organosilanes lab scale treatments had a WPG of 11% and showed the lowest dimensional stability (between 21 and 33%). Donath et al (2004) evaluated the stability of wood modified with several organosilanes and found WPG between about 10 and 25% and ASE values up to approximately 30% in treated beech wood. This is comparable to the values found in the present study. The inorganic lab scale treatments (Al and Mg) are the ones that show the highest humidity and immersion ASE (>50%) with a WPG of 4% for aluminum and 15% for magnesium treatment. Ximenes and Evans (2006) reported high ASE (between 45 and 105%) for Scots pine (*Pinus sylvestris* L.) sapwood treated with aluminum hydroxide and magnesium aluminate . Wang et al (2022) observed, for Chinese white poplar (*Populus* × *tomentosa* Carrière), dimensional stability in the radial and tangential direction of between 35 and 62% depending on the concentration of aluminum chloride ($AlCl_3$) used. These authors

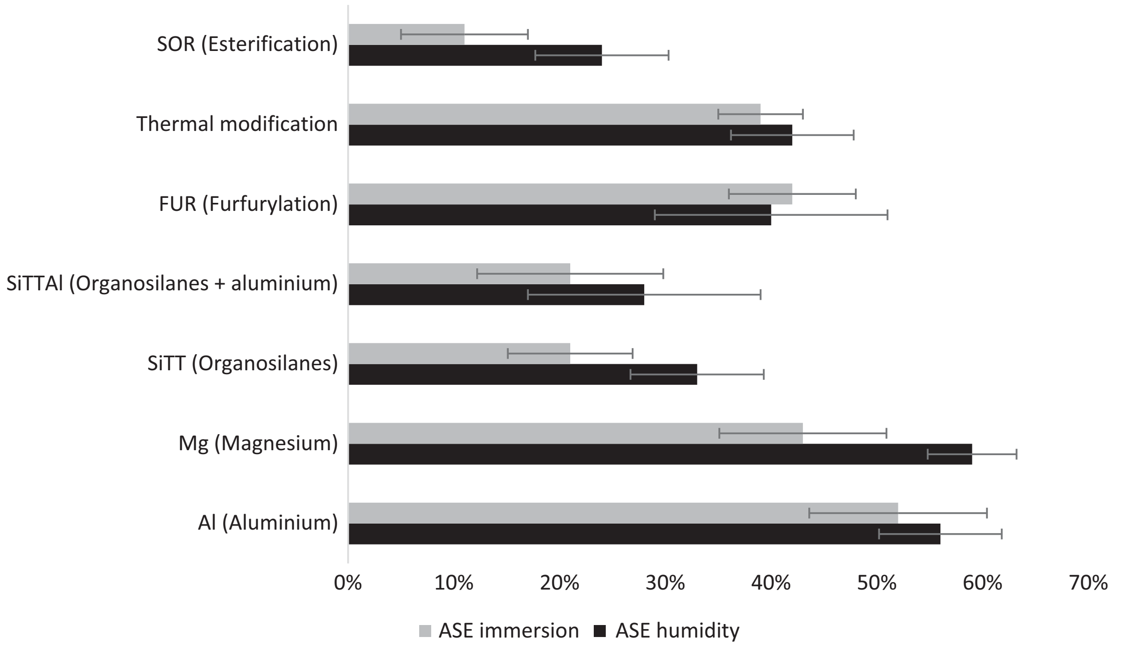


Figure 1. Average volumetric antiswelling efficiency (ASE) under humidity conditions and after immersion for white spruce treated with different treatments.

explained that the aluminum solution impregnated into the wood before treatment was used as a thermal catalyst. They concluded that the hydrolysis of polysaccharides was accelerated by $AlCl_3$ acid. Depolymerization and repolymerization of lignin in this $AlCl_3$ environment during heat treatment could be promoted. The high antiswelling efficiency observed for magnesium and aluminum treatment (43-59%) under humidity and immersion conditions for white spruce mixed heartwood and sapwood is similar to the results obtained in those studies.

For the commercial treatments, the highest stability was obtained with the FUR treatment and thermal modification (around 40%). The FUR modification of white spruce had an average WPG of 26% with volumetric ASE of 40% with changes in RH. There was considerable variability likely due to variation in the proportion of sapwood and heartwood within this specimen. In previous work on *Cryptomeria japonica* sapwood, Baysal et al (2004) reported an ASE of 85% at a WPG of 122%. In previous work on *Pinus pinaster*, Esteves et al (2011) reported an ASE of 46% at a WPG of 40%. Westin et al (2004) reported an ASE of 30-35% at a WPG of 15% for Scots pine sapwood. By increasing the WPG up to 47% in the furfurylated Scots pine, the ASE was up to 70% (Westin et al 2004). For Scots pine sapwood, Lande et al (2004) reported an ASE of approximately 50% at a WPG of 32%. Lande et al (2004) evaluated ASE at four different WPG levels and observed a correlation between WPG and ASE with higher uptakes associated with higher degrees of stabilization. The limited uptake achievable with white spruce will likely limit the degree to which the wood can be stabilized. However, based on the reported uptake, the ASE obtained for white spruce was slightly lower than that reported on other species. The present study did not control for the source of the white spruce evaluated. Previous research on Norway spruce has shown significant differences in furfuryl alcohol uptake based on the growth conditions, tree characteristics, location within the stem, and drying method (Lande et al 2010). Similar variations in white spruce may occur but were not assessed as part of the present work. The SOR modification of white spruce had an average WPG of 25% with volumetric ASE of 24% with changes in RH. Studies on European beech (*Fagus sylvatica*) sapwood at comparable WPG (22%) found ASE between 44 and 52% (Mubarok et al 2020). For Scots pine sapwood with sorbitol and citric acid, the ASE was 72% with a WPG of 62% (Schorr et al 2024). These are approximately double the ASE that we found in this study for the white spruce, which is explained because of the mixed sapwood and heartwood present in the white spruce samples studied.

Thermal modification showed slightly lower stability than the FUR treatment for refractory species but is still at 42% (humidity) and 39% (in immersion). Thermal modification is one of the most promising technologies for refractory species because it does not require the penetration of chemicals into the wood. The dimensional stability of refractory species can be significantly improved by thermal modification (Bekhta and Niemz 2003; Lekounougou and Kocaefe 2014). However, improvements in decay resistance are limited to above-ground applications, and the wood remains susceptible to termites (Shi et al 2007; Candelier et al 2017; Mubarok et al 2019).

Combined thermal modification and chemical treatments have been studied (Salman et al 2014; Wang et al 2018; Qu et al 2021) and may be able to overcome these technical challenges, though lower-cost solutions may be needed to commercialize this approach. Moreover, this approach would likely not be suitable for refractory species as the chemical pretreatments would still require deep penetration into the wood.

The use of chemical modification technologies remains confined to a few species with wide, permeable sapwood. The present work has shown that chemical modification technologies can improve wood properties in refractory species where full penetration is not achieved. However, this improvement may not be sufficient to meet end-user expectations or to compete with chemically modified permeable wood species. There is a lack of information on the degree of stabilization that is required for various applications. The development of performance-based standards for material stability could help to identify appropriate technologies for specific end users, and spur innovation of new products to meet these specifications.

Accelerated UV exposure. Wood surfaces are susceptible to photochemical degradation when exposed to weathering. Stable wood color is one of the most important requirements for cladding in North America. Figure 2 presents the Δa* for treated and untreated, finished, and unfinished samples from 0 h to 2000 h of accelerated UV exposure. Unfinished untreated and organosilanes-treated samples showed an increase in Δa* up to 250 h compared with the other samples, then a decrease in Δa*, becoming negative after 2000 h. In fact, all unfinished treated samples showed a lower negative Δa* after 2000 h than unfinished untreated wood, becoming greener with accelerated UV exposure. The finished esterified samples (SOR) also showed a negative Δa* after 2000 h compared with all other finished treated and untreated samples which maintained a Δa* greater than 0. Table 5 shows the total color change (ΔE*ab), ΔL*, Δa*, Δb* for treated and untreated, finished and unfinished samples after 2000 h of accelerated UV exposure. Tables 6 and 7 show the pictures of the unfinished and finished, treated and untreated white spruce samples. Most of the treatments studied resulted in a darkening of the wood. However, after accelerated aging, most materials had a similar color and appearance. The larger color changes associated with many of the treatments reflects the loss of color associated with the treatment rather than a greater change in the color of the underlying wood.

All treatments applied to white spruce negatively impacted the ΔE*ab when the samples were not finished with a stain. Unfinished samples show

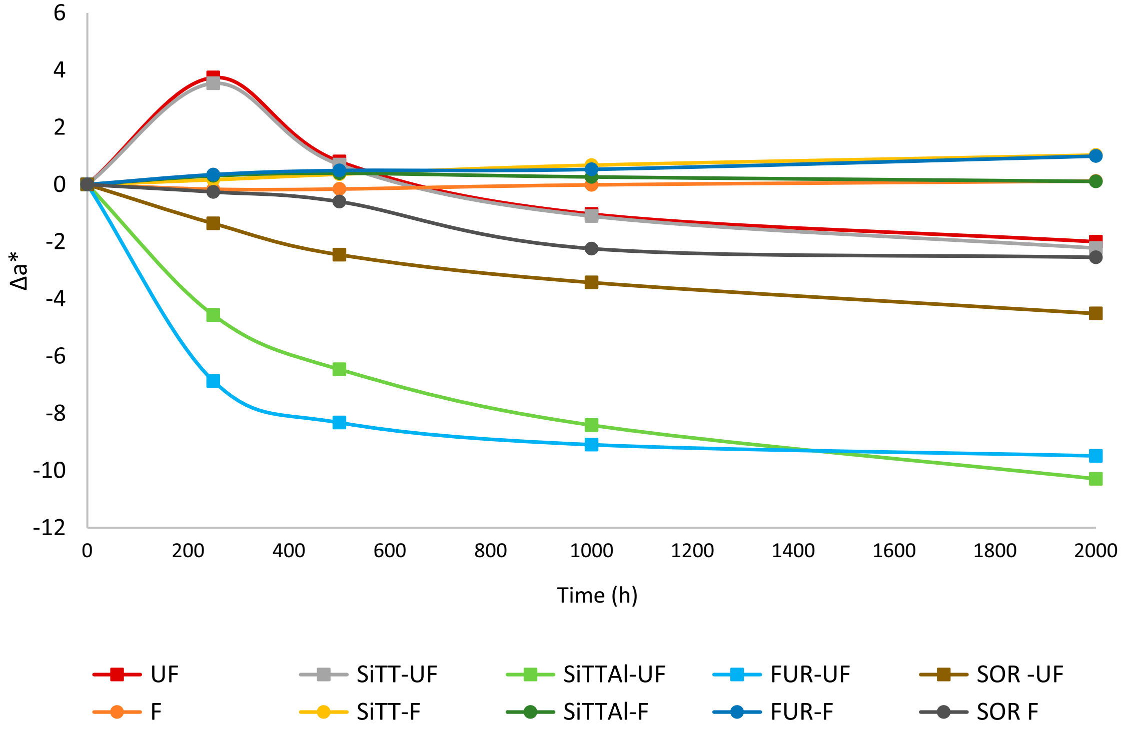


Figure 2. Δa* evolution for treated and untreated, finished (F) and unfinished (UF) white spruce samples over a period of 2000 h of accelerated UV exposure.

Table 5. Total color change (ΔE*ab), ΔL*, Δa*, Δb* for treated and untreated, finished and unfinished white spruce samples after 2000 h of accelerated UV exposure.

		Unfinished				Finished			
	Treatment	ΔEab*	ΔL*	Δa*	Δb*	ΔEab*	ΔL*	Δa*	Δb*
	Untreated	16.3	2.1	−2	−15.8	0.9	0.4	0.1	0.1
Lab scale treatment	Al (aluminum)	No data				No data			
	Mg (magnesium)	No data				No data			
	SiTT (organosilanes)	22.0	4.7	−2.2	−21.4	1.4	−0.4	1.0	0.3
	SiTTAl (organosilanes + aluminum)	39.5	31.2	−10.3	−21.4	1.5	−0.1	0.1	−0.2
Commercial treatment	FUR (furfurylation)	44.7	40.8	−9.5	−29.2	4.4	0.1	1.0	9.4
	Thermal modification	No data				No data			
	SOR (esterification)	21.4	13.8	−4.5	−15.5	3.3	−0.03	−2.6	−1.4

high ΔE*ab with values higher than 16. The highest ΔE*ab was obtained with the FUR treatment with a value of 44.7. Since the North American cladding market values color stability, even after UV exposure, the use of a semitransparent stain was important to assess whether the color change was limited to coated treated wood. The use of a semitransparent stain helped slow down the effect of photodegradation on treated and untreated samples and reduce ΔE*ab, especially for untreated

Table 6. Pictures of treated and untreated white spruce unfinished before and after 2000 h of accelerated UV exposure without semitransparent stain.

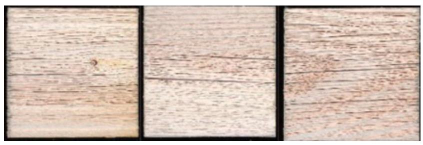
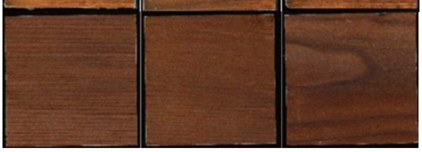
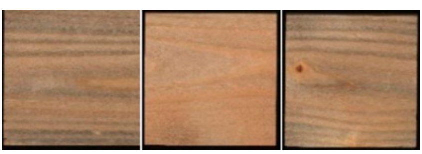
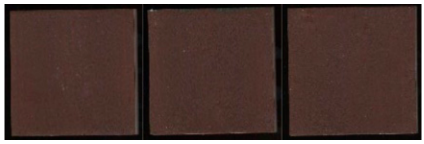
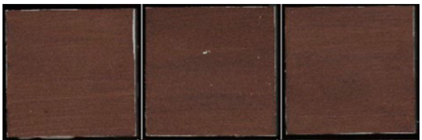
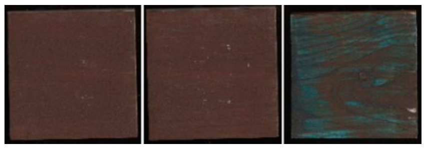
	Initial pictures	Pictures after 2000 h of UV exposure
Untreated		
Aluminum		
Magnesium		
SiTT (organosilanes)		
SiTTAl (organosilanes aluminum)		
Furfurylation		
Thermal modification		
SOR (esterification)		

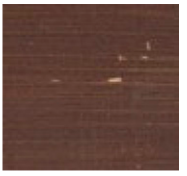
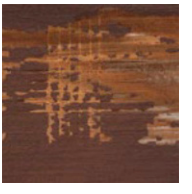
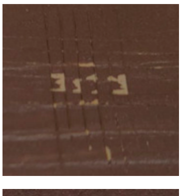
Table 7. Pictures of treated and untreated white spruce coated with a semitransparent stain before and after accelerated UV exposure.

	Initial pictures	Pictures after 2000 h of UV aging exposure
Untreated		
Aluminum		
Magnesium		
SiTT (organosilanes)		
SiTTAl (organosilanes + aluminum)		
Furfurylation		
Thermal modification		
SOR (esterification)		

and organosilanes treatment with ΔE*ab of 1 or 2. However, even with the semitransparent stain, both commercially finished treated wood (FUR and SOR) show a ΔE*ab > 3 that may be visible to the naked eye.

Coating adhesion. As accelerated UV exposure tests have shown in this study, all the treated white spruce wood studied should be finished to retain its color unchanged to the naked eye after at least 2000 h of accelerated UV exposure. However, to maintain good finish protection, coating adhesion must be good after application and after aging. For this reason, coating adhesion was an important test to perform on finished treated wood. Table 8 presents the stain adhesion values obtained for the various coated, treated white spruce samples. The untreated samples present the highest adhesion value. The only treatment that had fair adhesion, before UV exposure, was the FUR. Poor adhesion was obtained with the organosilanes treatment, as well as for thermal modification. All other treatments show no stain adhesion, even before exposure to UV. There was no value presented for the magnesium treatment as the stain was not adhering to the sample surface during sample preparation. After 2000 h of accelerated UV exposure, all treated samples showed no coating adhesion, whereas untreated samples still had fair adhesion. The treatments investigated may have increased the hydrophobicity of the wood surface which could reduce adhesion with the water-based semitransparent stain. In addition, mechanical anchoring may have been hampered by changes in lumen filling and, as Jaic et al (2014) presented in their study, adhesion

Table 8. Average adhesion of a semitransparent stain applied on treated and untreated white spruce.

	Average initial adhesion	Example of pictures before 2000 h of UV aging exposure	Average adhesion after 2000 h of UV aging exposure	Example of pictures after 2000 h
Untreated	4B		3B	
Aluminum	0B		—	—
Magnesium	—	—	—	—
SiTT (organosilanes)	2B		0B	
SiTTAl (organosilanes + aluminum)	0B		0B	
Furfurylation	3B		0B	
Thermal modification	2B		—	—
SOR (esterification)	0B		0B	

between an aqueous-phase coating and the wood substrate is primarily based on mechanical bonding (entanglement) compared with a solvent-based coating whose adhesion may be based on other bonding mechanisms.

CONCLUSIONS

The dimensional stability of white spruce boards containing a mixture of sapwood and heartwood was improved following cyclical exposure to high humidity and water immersion. The degree of stabilization varied within and between treatments and was generally lower than reported values for more permeable wood types, such as pine sapwood. All treatments were associated with greater color change than unmodified wood following accelerated UV exposure. The application of a semitransparent stain reduced the color change of the modified materials. However, all modifications were associated with greatly reduced stain adhesion. The limited improvement in stability and poor performance as a coating substrate limit the commercial applications for these technologies on white spruce. Further work is required to enhance the permeability of refractory species that resist chemical modification. Additionally, there is a need to identify or develop coatings that can adhere effectively to the wood modified by these treatments.

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