coatings

Article

Coating Performance on Exterior Oil-Heat Treated Wood

Mojgan Nejad [1,*], Mahdi Dadbin [2] and Paul Cooper [2]

[1] Department of Forestry, Michigan State University, 480 Wilson Road, East Lansing, MI 48824, USA
[2] Faculty of Forestry, University of Toronto, 33 Willcocks St., Toronto, ON M5S 3E8, Canada; mdadbin@gmail.com (M.D.); p.cooper@utoronto.ca (P.C.)
* Correspondence: nejad@msu.edu; Tel.: 1-517-355-9597

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Abstract: Thermal modification and the degree of improved properties from the treatment depend on wood species and treatment parameters. Southern yellow pine and spruce are two wood species commonly used for decking, fences, and siding in North America. This study evaluated coating performance when applied on oil-heat-treated Southern pine and spruce wood samples. Moisture content, color, and gloss changes of samples were analyzed before weathering and then after each month for the first three months and then every six months during 18 months of natural weathering exposure in Toronto, Canada. The results showed that coated heat-treated woods had lower moisture uptake, lower color change, and overall better appearance ranking than coated-untreated wood samples. Coated-spruce wood samples had lower checking and splitting, and in general, much better performance than coated-Southern pine treated samples. Notably, the average moisture content of treated spruce wood samples was significantly lower than that of Southern pine, which explains lower checking and improved coatings' appearance.

Keywords: wood coating; natural weathering; thermal treatment; wood modification

1. Introduction

Thermal treatment is a wood modification process that is used to improve the durability of wood in exterior applications without using any chemicals. Wood is treated at high temperatures under an oxygen-free environment to avoid oxidation of wood components. Thermal treatment is considered an environmentally friendlier technique than preservative treatments because it does not require any chemicals for treatment and treated woods are completely safe to be burned after their service life. There have been growing concerns in regards to landfilling of chromated copper arsenate (CCA) treated-wood and the possibility of arsenic and chromium transfer to the underground body of water or rivers through storm runoff water from landfill areas [1]. This might be even more problematic with Cu-based treated wood, because aquatic organisms are very sensitive to copper, and the copper amount is much higher in Cu-based preservatives than in CCA [2,3]. The other concern with preservative treated wood is that the heavy metals also leach from pressure treated wood to the surrounding environment during service [4–6]. This was the main reason that the wood preservative industry voluntarily shifted from CCA-treated wood to Cu-based preservative treatment for residential applications in 2005 [5]. The main concern for potential exposure of human for CCA was related to arsenic and chromium, but for the aquatic environment, copper is detrimental [7,8]. Although thermally treated wood provides some degree of protection against decay and insect attack, it is not adequate to protect the wood in contact ground applications [9–11]. For residential applications where the wood is not in direct contact with the ground, thermally treated wood is a great candidate for applications like decking, fences, and siding.

One of the main advantages of thermal treatment is the dimensional stability of wood after modification. Wood is a hygroscopic material, which means it readily absorbs moisture. Thermal modification at a temperature above 180 °C is reported to increase the dimensional stability of the wood significantly [12–14]. At that high temperature, hemicelluloses and lignin structures in the wood will go through irreversible changes that make this effect permanent in the wood [11,15]. Nuopponen et al. [16] reported that the degradation of hemicelluloses and the dehydration reaction resulted in a major reduction of hydroxyl groups in wood. Hydroxyl functional groups in wood are responsible for attracting water molecules by creating hydrogen bonds with water, either from moisture in the air or by absorbing liquid water through rain and snow. Higher dimensional stability of wood translates to less swelling, less checking, and cracking; thus, in general, they should create fewer stresses for a coating's film [17–20].

There are two major developed industrial methods for thermally treating wood. One is by using steam, and the other is by using hot-oil. The oil will act as a heating medium to uniformly transfer the heat throughout the wood thickness [19,21,22]. A number of studies reported that heat-treatment changes the wettability of wood by increasing the crystallinity of cellulose and lignin plasticization, which raises the question of how these changes to the surface properties of the wood would affect the coating performance on treated wood when exposed to natural weathering. In the oil-heat treatment process, oil-uptake and deep penetration of oil into the wood is also a concern as it might affect the coating's adhesion and performance [12,13].

Kocafe and Saha [18] studied the effect of the addition of different UV-stabilizers (bark extract, lignin, and organic UV-stabilizer) on reducing accelerated aging of acrylic polyurethane coatings on three heat-treated North American wood species (birch, jack pine, and aspen). Their results showed that the degradation was not due to the coating adhesion loss but rather it was related to the degradation of heat-treated wood under the coating layer. Kesik et al. [20] investigated the weathering performance of one varnish and one paint formulation when applied on heat-treated scots pine and fir during one year of natural weathering in Turkey. They reported that varnished heat-treated wood had better performance (color change and hardness) than varnished untreated wood samples, while painted samples had similar performance on both heat-treated and untreated wood. Jamsa et al. [16] studied the weathering performance of four different coating formulations when applied on spruce and pine steam-heat treated woods during 5 years of natural exposure in Finland. They also found that acid curable and water-borne acrylic paint had better performance with less cracking on heat-treated wood samples than they did on untreated wood. Altgen and Militz [23] studied the adhesion and penetration of coatings into steam heat-treated scots pine and Norway spruce and showed while the contact angle of coatings increased on thermally modified wood (TMW), the penetration of coatings into TMW were similar to untreated wood samples.

The main goal of this study was to compare the effect of oil-heat-treatment on spruce and Southern yellow pine wood samples, which are the most common wood species used in decking applications in Canada and the United States. Another objective was to monitor and evaluate the performance of a wide range of both water-based and solvent-based coatings when applied on oil-heat-treated woods during eighteen months of natural weathering exposure in Canada.

2. Materials and Methods

Sixteen planed flat sawn spruce (*Picea mariana; Picea glauca)* boards measuring (1.5 cm × 8 cm × 240 cm) were purchased from Home Depot. The wood samples were cut in half; one half was kept as control, and the other half was cut into two pieces that could fit into an oil bath for thermal treatment.

The Southern yellow pine (*Pinus sp.)* boards were all radially cut (available in the lab) and included both heartwood and sapwood. Twelve boards of 3.5 cm × 13 cm × 60 cm were cut in half. Similarly, one set was kept as control (untreated samples) and the other set was heat-treated.

Wood samples were placed in a hot-oil bath containing soybean oil with 10% wax (at temperature around 80 °C) and gradually heated up to 210 °C and then held at that temperature for three hours.

Then they were stored in the oven at 100 °C overnight to be cured and gradually cooled down. After 24 h, samples were taken out of the oven and kept in the lab to condition before planing to have smooth, oil-free surface before coating. All samples were sanded with 100 grit sandpaper and wiped with a damp cloth an hour before application of the coating.

Nine different formulations of exterior penetrating stains (eight semi-transparent and one transparent) were purchased or obtained directly from manufacturers. Out of these nine formulations, two were solvent-based, and seven were water-based formulations. The detailed information about coatings' type and their measured properties are shown in Table 1.

Coating were applied using foam brushes. Based on the density of each coating and surface area of wood samples, the amount of applied coating on each sample was accurately calculated to make sure that all samples had the same wet film thickness to ensure a fair comparison. The densities of coatings were measured using a hydrometer. The weight was adjusted to have a total of 0.12 mm wet film thickness in two coats applications based on the coating's density and wood surface area. Coating number one was an exception, as it was recommended for one coat application; all other coatings were applied twice to have two coats at different times following the exact procedure as recommended by the manufacturer (details are noted in Table 1).

The viscosities of coatings were measured using a Brookfield digital viscometer at 20 rpm using spindle number 1 for most coatings and number 2 for two of them (three replicates measurements for each coatings were evaluated). The solid contents of coatings were analyzed according to ASTM D2369 by placing about 2 mL of each coating on an aluminum pan and heating in the oven at 110 °C for one hour (three replicates).

The end grain of all spruce and Southern pine wood samples were sealed using a high viscosity white epoxy paint. After the application of coatings was finished, all samples were left in the lab to air dry for one week (around 20 °C and 50% RH), and their weights were measured right before natural weathering study for moisture content analysis.

The color, gloss, and weight of samples were measured before weathering and every month for the first three months and then every six months for up to 18 months during natural weathering testing. The color of samples was measured using a Konica Minolta spectrophotometer CM-2002 (Tokyo, Japan) in SCE mode (specular component excluded) according to ASTM D2244 [24]. The ΔE color change was calculated according to the following equation:

$$\Delta E \ = \ \sqrt{(L2 - L1)^2 + +(a2 - a1)^2 + (b2 - b1)^2}, \qquad (1)$$

The gloss of the samples was measured with a glossmeter at 20°, 60°, and 85° angles. Checking (ASTM D660 [25]), flaking (ASTM D772 [26]), fungal growth (ASTM D3274 [27]), coating erosion (ASTM D662 [28]) and general appearance of coated-wood samples were evaluated every six months according to noted standard test methods with a 10 rating being the best (perfect condition) with no visible defect, and zero being worst with many defects or complete failure. The samples were placed on a metal mesh rack horizontally exposed to direct sun and rain for 18 months on the roof of the Forestry building at the University of Toronto, Canada.

All data were analyzed using two-way ANOVA and Tukey grouping with SAS software (version 9.4) to statistically compare the effects of coatings, wood species, and treatment on each evaluated performance parameter of coated-treated or untreated wood samples after long-term direct exposure to sun and rain.

3. Results and Discussion

Coating properties and detailed information about their applications are presented in Table 1. Except coating number 5 that was transparent, all other coatings were semi-transparent formulations.

Table 1. Measured coating properties and application details.

Coating ID	Resin	Base	Density	% Solid Content	Viscosity (mPa.s)	Number of Coats and Application	
1-Al-S	Alkyd	Solvent	0.87	40 ± 2	73 ± 1	1	Only one coat
2-Al-S	Alkyd	Solvent	0.96	63 ± 2	1004 ± 10	2	After 16 h
3-Al-W	Alkyd	Water	1.01	30 ± 2	882 ± 3	2	After 20 min
4-Ac-W	Acrylic	Water	1.02	10 ± 0.0	21 ± 4	2	Wet on wet
5-Al-W	Alkyd	Water	1.01	10 ± 0.1	213 ± 1	2	Before 2 h
6-Al-Ac-W	Alkyd- Acrylic	Water	1.04	24 ± 0.1	24 ± 1	2	After 24 h
7-Al-Ac-W	Alkyd-Acrylic	Water	1.03	24 ± 2	23 ± 1	2	After 24 h
8-Ac-W	Acrylic	Water	1.05	25 ± 2	352 ± 4	2	After 24 h
9-Ac-W	Acrylic	Water	1.03	23 ± 1	59 ± 2	2	After 24 h

3.1. Moisture Content

The average moisture contents of uncoated-treated and untreated spruce and Southern pine samples are shown in Figure 1. As expected, heat-treated wood had significantly lower moisture uptake than untreated wood, but interestingly, there was a significant difference between the average MC of the heat-treated spruce (9 ± 0.6) and Southern pine (13 ± 1.0), presumably because of the higher permeability of the Southern pine sapwood or due to the fact that yellow pine samples were twice as thick as spruce wood samples.

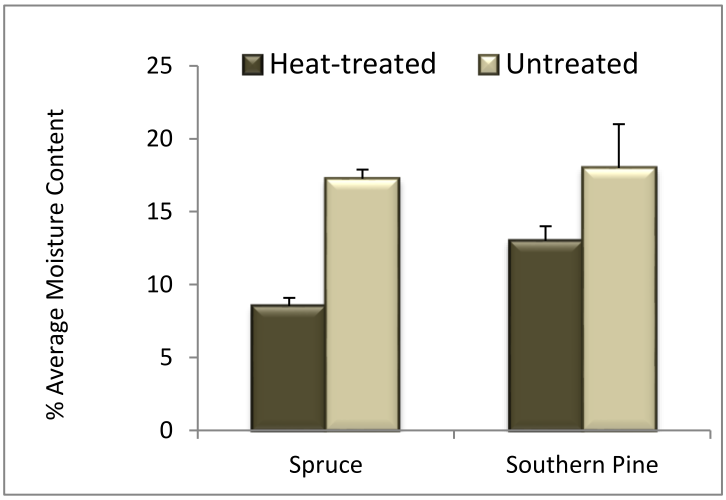

Figure 1. Percent average moisture content of uncoated, heat-treated, and untreated spruce and Southern yellow pine samples.

Figure 2 shows the average moisture contents of coated and uncoated samples on both heat-treated and untreated spruce samples after 18 months of natural weathering. As can be seen, all heat-treated samples, whether coated or uncoated, had significantly lower moisture uptake than un-treated wood samples as also reported by previous studies [29,30]. There are some variations between coatings and differences in their performance; however, based on two-way ANOVA results, the differences are not statistically significant.

The average moisture contents of coated and uncoated heat-treated pine samples were also significantly lower than the average moisture contents of untreated samples (not shown here). However, the difference between the MC of heat-treated pine with untreated pine was slightly lower than the difference between heat-treated spruce and untreated spruce samples shown as uncoated samples in Figure 1.

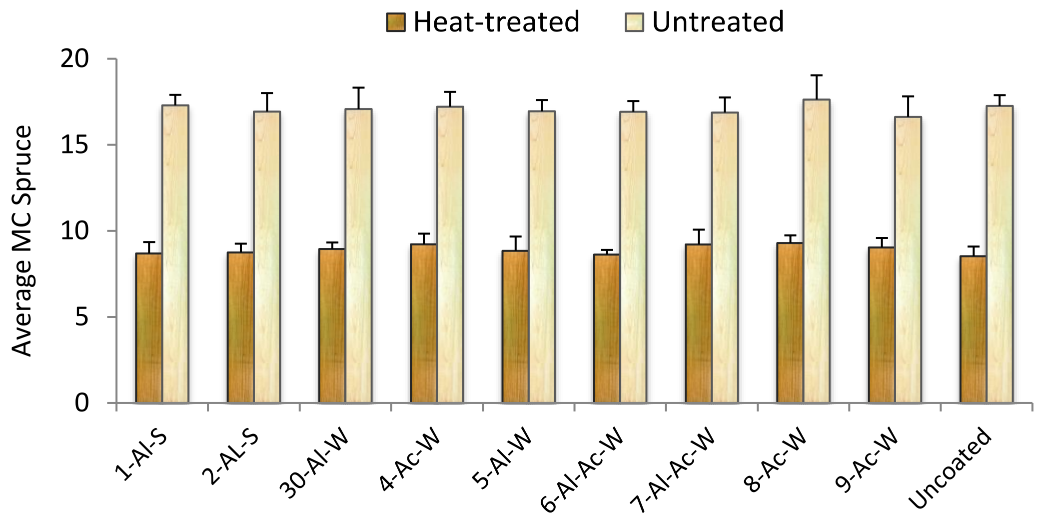

Figure 2. The percent average moisture content of coated and uncoated, heat-treated and untreated spruce samples during 18 months of natural weathering.

3.2. Color Change

The color change of samples after 18 months of natural weathering of both wood species are shown in Figure 3. Although there is not much difference between the color change of heat-treated and untreated wood for uncoated samples, it is clearly apparent that coated-heat-treated wood samples had much less color change than coated untreated woods as reported previously for the effect of stain on heat-treated wood [20]. It seems that the coating significantly enhanced the performance of heat-treated wood, regardless of wood species.

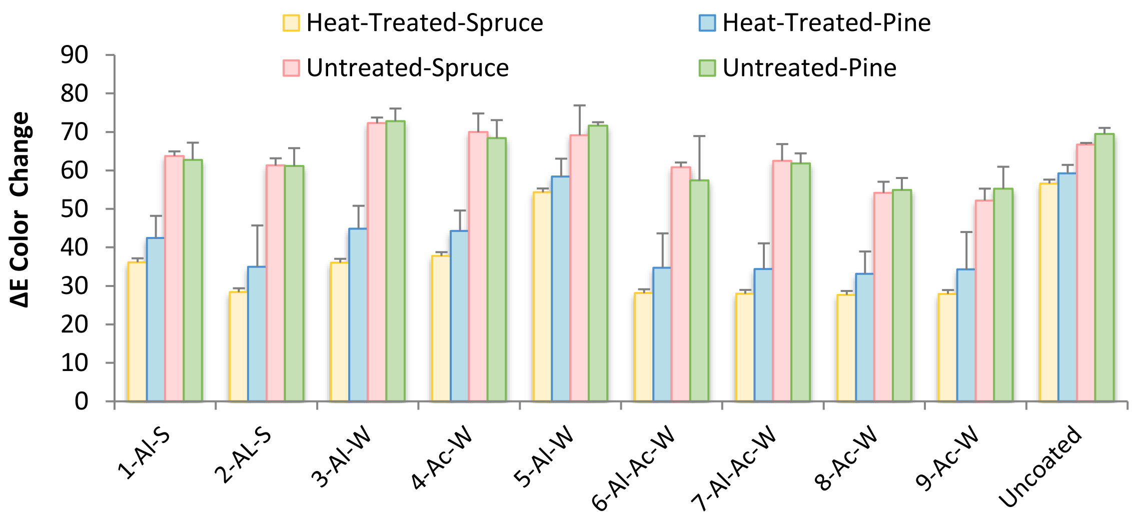

Figure 3. Maximum color change (ΔE) of coated and uncoated, heat-treated and untreated Southern pine (SYP) and spruce wood samples after natural weathering.

A more detailed look at the changes in L^* a^* b^* color coordinates of spruce samples before and after natural weathering clearly shows (Table 2) that heat-treated spruce samples had significantly lower ΔL than untreated samples. As expected, after heat-treatment, the wood surface became much darker, thus changing the lightness (L value) from 92 to 59 on average. This initial lower lightness of the treated wood can explain the lower ΔL value after weathering. The Δa change of both heat-treated and untreated wood samples whether coated and uncoated were very similar (on average the a^* value changed from 23 to 21 after heat-treatment). Since Δa represents the color change from green to red, both the untreated and heat-treated sample shifted to the same level toward greener color (-a) after weathering. On the other hand, the Δ*b* values, which indicate color changes from yellow to blue, of heat-treated samples were significantly lower than for the untreated samples. Looking at the initial color of heat-treated samples, the average b* value of spruce samples changed from 60 to 35 after heat-treatment, which is a substantial shift toward bluer color. Therefore, when wood turns to grey after weathering, we will see less color change of heat-treated wood. This is because the initial color coordinate data of the treated wood (average $L = 59$, $a = 21$, $b = 35$) is closer to the grey color (average $L = 53$, $a = -8$ and $b = 20$) than to the initial color of untreated wood samples (average $L = 92$, $a = 23$ and $b = 60$). This analysis shows that although the observation of color change shows that heat-treated wood has less color change than untreated wood samples, it is only due to differences in the initial color of heat-treated wood, which is closer to the grey color of weathered wood.

Table 2. The color change of coated and uncoated, treated and untreated spruce and pine wood samples after 18 months of natural weathering.

Paint Color	Untreated Spruce ΔL	Δa	Δb	ΔE	Heat−Treated Spruce ΔL	Δa	Δb	ΔE
1−Al−S	−37 ± 2	−32 ± 3	−41 ± 3	64 ± 1	6 ± 2	−35 ± 1	−8 ± 2	36 ± 1
2−Al−S	−29 ± 4	−31 ± 1	−43 ± 6	61 ± 5	−3 ± 6	−27 ± 1	−4 ± 2	28 ± 2
3−Al−W	−44 ± 3	−33 ± 3	−46 ± 3	72 ± 2	−3 ± 3	−34 ± 1	−12 ± 1	36 ± 1
4−Ac−W	−39 ± 3	−32 ± 4	−46 ± 2	68 ± 1	−12 ± 2	−31 ± 1	−17 ± 5	38 ± 4
5−Al−W	−49 ± 2	−30 ± 1	−38 ± 2	69 ± 2	−7 ± 3	−35 ± 5	−37 ± 4	52 ± 6
6−Al−Ac−W	−28 ± 5	−33 ± 1	−43 ± 2	61 ± 3	−9 ± 1	−24 ± 1	−10 ± 1	28 ± 1
7−Al−Ac−W	−31 ± 3	−35 ± 1	−42 ± 3	62 ± 3	−9 ± 2	−24 ± 2	−11 ± 4	28 ± 4
8−Ac−W	−30 ± 1	−31 ± 1	−33 ± 1	54 ± 1	−5 ± 2	−26 ± 2	−6 ± 3	28 ± 2
9−Ac−W	−29 ± 2	−29 ± 1	−32 ± 1	52 ± 1	−6 ± 2	−27 ± 2	−5 ± 3	28 ± 3
Uncoated	−52 ± 1	−29 ± 1	−30 ± 1	67 ± 1	−22 ± 3	−34 ± 1	−39 ± 1	57 ± 1

Statistical analysis of color data indicates that effect of treatment ($\alpha < 0.0001$), wood species ($\alpha = 0.0025$) and coatings ($\alpha < 0.0001$) were all significant. The average color change of all spruce samples (coated, uncoated, treated and untreated) is about 49.7, which is significantly lower than the average color change of all Southern yellow pine samples of 52.8. Heat-treated spruce wood whether coated or uncoated, on average (36.1) had much lower color change than untreated-wood samples (63.3). Table 3 shows the two-way ANOVA result of maximum color change data. Although not statistically significant, coating number 5, which was a transparent coating, had slightly higher color change (63.8) than the uncoated samples (63.4).

Table 3. Tukey grouping of maximum color changed data after 18 months of weathering (means with the same letter are not significantly different).

Tukey Grouping		Mean	N	Coating
–	A	63.8	16	5
–	A	63.4	16	Uncoated
B	A	57.1	16	3
B	–	55.5	16	4
B	C	51.6	16	1
D	C	47.0	16	7
D	C	46.8	16	2
D	C	45.5	16	6
D	–	42.3	16	9
D	–	42.9	16	8

3.3. Gloss Change

The radar chart in Figure 4 shows the gloss changes in Southern pine samples after 18 months of natural weathering. All coated and uncoated samples lost gloss, as the data shows in the negative values. It clearly shows that there is an interaction effect between solvent-based coatings and untreated woods. The solvent-based coatings number 1 and 2 have much lower gloss changes on untreated wood samples than they did on heat-treated woods, while water-based coatings had similar performance on both heat-treated and untreated wood samples. Overall, water-based coatings had a lower gloss change than solvent-based coatings. The two solvent-based coatings used in this study had much higher initial gloss (15 at 60°) than the water-based coatings (7) on pine, while the final gloss of the coated samples for both solvent-based and water-based coatings were 3. Thus, we observed a higher gloss change for solvent-based coatings after 18 months of natural weathering on Southern pine samples, because their initial gloss data was higher.

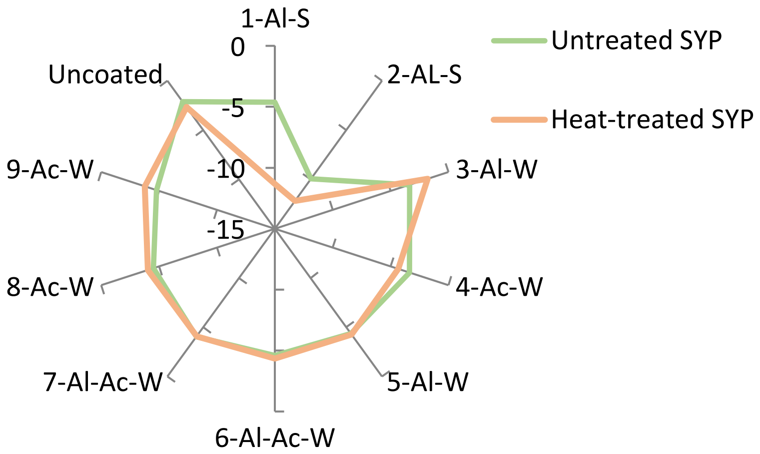

Figure 4. Radar chart of maximum gloss change of coated and uncoated, heat-treated and untreated Southern pine samples after natural weathering.

3.4. Appearance Ranking

Table 4 summarizes the average appearance ranking of all wood samples, treated and untreated, coated and uncoated, for both spruce and Southern yellow pine samples. The analysis of average ranking data of checking of wood, erosion of coating from the surface of wood, mildew coverage of the surface of the wood, and general appearance of either coated or uncoated wood samples with two-way ANOVA were performed using SAS software. The results show that there was a significant difference between the two wood species; Southern yellow pine wood samples (5.1) overall had worse appearance rankings than spruce (5.8). Southern yellow pine has an overall higher density than spruce and more prominent earlywood/latewood differences, and it was expected that coatings would have better overall performance on spruce than Southern pine samples.

There were also significant differences among performances of coatings on heat-treated woods compared to untreated woods. Heat-treated woods (5.5) on average had better rankings than untreated woods (5.1). Heat-treated wood samples during their 18 months of weathering exposure had much lower moisture uptake than untreated woods. For instance, the average MC of spruce untreated samples (both coated and uncoated) initially was 28, while the average MC of spruce treated samples was 14 (100% lower), and after 18 months of natural weathering, the average MC of spruce untreated samples (again coated and uncoated) was 12, while that of heat-treated samples was 6.6 (80% lower). This lower moisture uptake explains their dimensional stability, which in turn translates to lower stresses for coatings. This is the main reason that we observed relatively less erosion of coatings and less checking of the heat-treated wood. Also, the color stability of heat-treated wood was better than untreated woods, which also clarifies why the treated wood had a better appearance ranking than untreated woods (Figures 5 and 6).

Table 4. Ranking of coated-treated, untreated, and uncoated wood samples after 18 months of natural weathering. The ranking 10 is the best with no visible defect, and 0 indicates a complete failure. The average of three replicates ± standard deviation is shown.

Treatment	Coatings	Southern Pine				Spruce			
		Checking	Mildew	Erosion	General	Checking	Mildew	Erosion	General
Untreated	1-Al-S	4 ± 1	4 ± 1	3 ± 1	3 ± 1	7 ± 1	7 ± 2	2 ± 0	3 ± 1
	2-Al-S	7 ± 2	6 ± 1	6 ± 1	6 ± 2	9 ± 1	9 ± 1	9 ± 1	8 ± 2
	3-Al-W	5 ± 1	3 ± 1	2 ± 1	2 ± 0	7 ± 3	4 ± 0	3 ± 1	2 ± 0
	4-Ac-W	4 ± 0	7 ± 4	0 ± 0	1 ± 2	5 ± 3	10 ± 0	0 ± 0	1 ± 1
	5-Al-W	4 ± 1	5 ± 5	0 ± 0	1 ± 1	7 ± 4	10 ± 0	1 ± 1	2 ± 2
	6-Al-Ac-W	8 ± 1	7 ± 3	6 ± 2	6 ± 2	6 ± 4	7 ± 1	4 ± 0	3 ± 1
	7-Al-Ac-W	6 ± 2	7 ± 1	6 ± 1	6 ± 0	7 ± 3	8 ± 2	6 ± 0	5 ± 2
	8-Ac-W	6 ± 2	6 ± 2	4 ± 1	5 ± 1	7 ± 2	9 ± 1	7 ± 1	5 ± 1
	9-Ac-W	7 ± 1	6 ± 1	6 ± 1	6 ± 1	9 ± 1	9 ± 1	7 ± 1	6 ± 2
	Uncoated	5 ± 2	8 ± 2	0 ± 0	5 ± 1	7 ± 3	10 ± 0	0 ± 0	5 ± 2
Heat-treated	1-Al-S	7 ± 1	5 ± 2	4 ± 1	4 ± 1	9 ± 1	8 ± 0	2 ± 0	2 ± 0
	2-Al-S	7 ± 1	9 ± 1	7 ± 1	7 ± 1	9 ± 1	10 ± 0	10 ± 0	8 ± 0
	3-Al-W	5 ± 11	2 ± 1	1 ± 1	1 ± 1	7 ± 4	5 ± 1	5 ± 1	2 ± 0
	4-Ac-W	5 ± 1	9 ± 1	0 ± 0	1 ± 1	6 ± 3	0 ± 0	0 ± 0	2 ± 0
	5-Al-W	6 ± 1	9 ± 1	0 ± 0	1 ± 1	7 ± 4	0 ± 0	0 ± 0	2 ± 0
	6-Al-Ac-W	7 ± 1	8 ± 1	6 ± 1	6 ± 1	9 ± 1	9 ± 1	8 ± 0	7 ± 1
	7-Al-Ac-W	7 ± 1	8 ± 0	6 ± 0	6 ± 1	10 ± 0	8 ± 0	7 ± 1	7 ± 1
	8-Ac-W	7 ± 2	8 ± 1	6 ± 1	6 ± 1	7 ± 4	7 ± 1	8 ± 0	6 ± 0
	9-Ac-W	7 ± 2	8 ± 1	7 ± 1	6 ± 2	8 ± 3	8 ± 0	8 ± 0	7 ± 1
	Uncoated	4 ± 1	9 ± 1	0 ± 0	5 ± 1	7 ± 4	0 ± 0	0 ± 0	2 ± 0

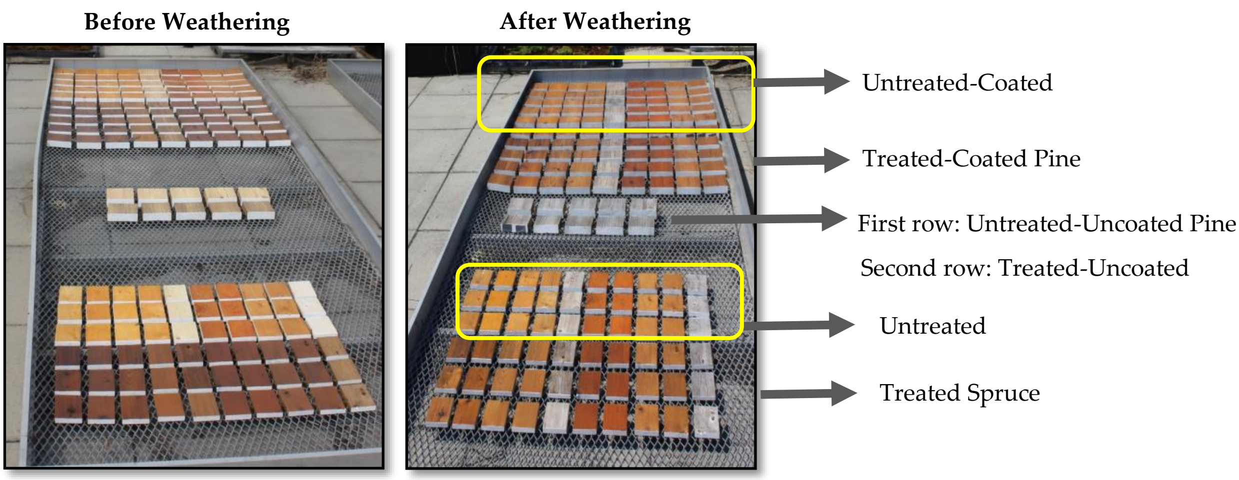

Figure 5. Samples before and after 18 months of natural weathering (the last column of the spruce set is uncoated samples).

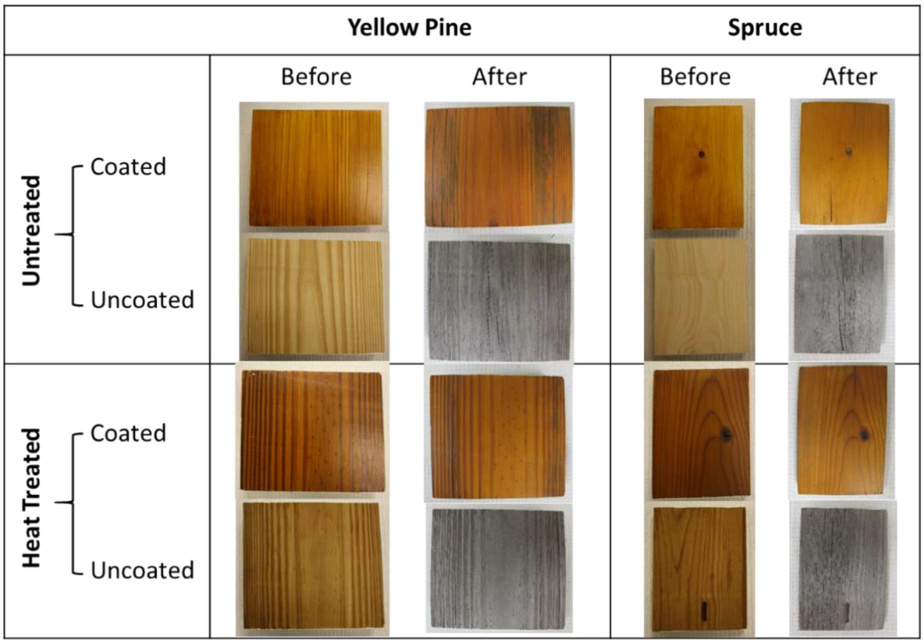

Figure 6. A close image of a coated sample (coating 2, alkyd solvent-based) and uncoated pine and spruce heat-treated and untreated wood samples before and after 18 months of natural weathering.

Table 5 shows the results of two-way ANOVA and Tukey grouping among the effects of coating on general rankings of samples. It is interesting that some coated-wood samples were ranked similar to or slightly lower than uncoated wood samples. There is not a clear correlation between observed performance and measured coating properties. For instance, no separation based on resin type or resin base (water-based vs. solvent-based) explains the grouping of the coatings. Performance evaluations are very subjective and extremely dependant on the wood properties, such as the density of the wood; more in-depth data analysis is needed, such as multivariate modeling, to identify underlying effects that could explain or find a possible correlation between coating properties and performance.

Table 5. The Tukey grouping of the average appearance rankings of coated and uncoated-treated and -untreated samples on both spruce and Southern pine samples (means with the same letter are not significantly different).

Tukey Grouping	Mean	N	Coating	Base
A	7.5	15	2	Solvent
	7.1	15	9	Water
A	6.7	15	7	Water
A	6.6	15	6	Water
A	6.4	15	8	Water
B	4.4	15	1	Solvent
B	4.4	15	Uncoated	—
B	3.4	15	5	Water
B	3.3	15	4	Water
	3.1	15	3	Water

4. Conclusions

Although oil-heat-treatment is not widely used at the commercial scale in North America, it has good potential to offer a pesticide-free way to protect wood for exterior applications. Treatments will change the surface properties of the wood, and this study provided some insight into how different coating formulations that are available in the North American market will perform on oil-heat-treated wood species that are commonly used in decking in the United States and Canada. Our results showed that oil-heat-treatment enhanced coating performance by improving its water resistance, color stability, and overall better general appearance ranking. Water-based coatings had a lower gloss change than solvent-based coatings. In addition, there was no indication that solvent-based coatings perform better than water-based coatings. This finding is especially important since there was some concern that oil-treatment might negatively affect the adhesion of the water-based coating to the wood.

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Conflicts of Interest: The authors declare no conflict of interest.

References

1. Taylor, J.L. Effect of Exposure Conditions on Leaching of Chromated Copper Arsenate, CCA-C, from Treated Wood. Master's Thesis, University of Toronto, Toronto, ON, Canada, September 2001.
2. Temiz, A.; Yildiz, U.C.; Nilsson, T. Comparison of copper emission rates from wood treated with different preservatives to the environment. *Build. Environ.* **2006**, *41*, 910–914. [CrossRef]
3. Flemming, C.A.; Trevors, J.T. Copper toxicity and chemistry in the environment: A review. *Water. Air Soil Pollut.* **1989**, *44*, 143–158. [CrossRef]
4. Robinson, B.; Greven, M.; Green, S.; Sivakumaran, S.; Davidson, P.; Clothier, B. Leaching of copper, chromium and arsenic from treated vineyard posts in Marlborough, New Zealand. *Sci. Total Environ.* **2006**, *364*, 113–123. [CrossRef]
5. Lebow, S. Leaching of Wood Preservative Components and Their Mobility in the Environment: Summary of Pertinent Literature. 1996; 36.
6. Khan, B.I.; Jambeck, J.; Solo-Gabriele, H.M.; Townsend, T.G.; Cai, Y. Release of arsenic to the environment from CCA-treated wood. 2. Leaching and speciation during disposal. *Environ. Sci. Technol.* **2006**, *40*, 994–999. [CrossRef]
7. Stook, K.; Tolaymat, T.; Ward, M.; Dubey, B.; Townsend, T.; Solo-Gabriele, H.; Bitton, G. Relative leaching and aquatic toxicity of pressure-treated wood products using batch leaching tests. *Environ. Sci. Technol.* **2005**, *39*, 155–163. [CrossRef] [PubMed]
8. Sunda, W.G.; Tester, P.A.; Huntsman, S.A. Effects of cupric and zinc ion activities on the survival and reproduction of marine copepods. *Mar. Biol.* **1987**, *94*, 203–210. [CrossRef]
9. Metsä-Kortelainen, S.; Paajanen, L.; Viitanen, H. Durability of thermally modified Norway spruce and Scots pine in above-ground conditions. *Wood Mater. Sci. Eng.* **2011**, *6*, 163–169. [CrossRef]
10. Metsä-Kortelainen, S.; Viitanen, H. Effect of fungal exposure on the strength of thermally modified norway spruce and Scots pine. *Wood Mater. Sci. Eng.* **2010**, *5*, 13–23. [CrossRef]
11. Esteves, B.M.; Pereira, H.M. Wood modification by heat treatment: A review. *BioResources* **2009**, *4*, 370–404.
12. Awoyemi, L.; Cooper, P.A.; Ung, T.Y. In-treatment cooling during thermal modification of wood in soy oil medium: soy oil uptake, wettability, water uptake and swelling properties. *Eur. J. Wood Wood Prod.* **2009**, *67*, 465. [CrossRef]
13. Dubey, K.M. Improvements in Stability, Durability and Mechanical Properties of Radiata Pine Wood after Heat-Treatment in a Vegetable Oil. Ph.D. Thesis, University of Canterbury, Christchurch, New Zealand, May 2010; pp. 1–211.
14. Stamm, A.J.; Hansen, L.A. Minimizing wood shrinkage and swelling effect of heating in various gases. *Ind. Eng. Chem.* **1937**, *29*, 831–833. [CrossRef]
15. Wikberg, H.; Maunu, S.L. Characterisation of thermally modified hard- And softwoods by 13C CPMAS NMR. *Carbohydr. Polym.* **2004**, *58*, 461–466. [CrossRef]
16. Nuopponen, M.; Vuorinen, T.; Jámsä, S.; Viitaniemi, P. Thermal modifications in softwood studied by FT-IR and UV resonance Raman spectroscopies. *J. Wood Chem. Technol.* **2004**, *24*, 13–26. [CrossRef]
17. Jämsä, S. Long-term natural weathering of coated ThermoWood. *Pigment Resin Technol.* **2000**, *29*, 68–74. [CrossRef]

18. Kocaefe, D.; Saha, S. Comparison of the protection effectiveness of acrylic polyurethane coatings containing bark extracts on three heat-treated North American wood species: Surface degradation. *Appl. Surf. Sci.* **2012**, *258*, 5283–5290. [CrossRef]
19. Esteves, B.M.; Domingos, I.J.; Pereira, H.M. Pine wood modification by heat treatment in air. *BioResources* **2008**, *3*, 1.
20. Kesik, H.I.; Özkan, O.E.; Öncel, M. Characteristics of a protective layer on oil heat-treated scots pine and fir wood. *BioResources* **2017**, *12*, 3067–3075. [CrossRef]
21. Wang, J.; Cooper, P. Review of Thermal Treatment of Wood. In Proceedings of the Canadian Wood Preservation Association, Halifax, NS, Canada, 28–29 October 2003; pp. 160–176.
22. Rapp, A.O.; Sailer, M. Heat treatment of wood in Germany-state of the art. In Proceedings of the seminar on production of heat treated wood in Europe, Hamburg, Germany, 1–4 January 2000; Vol. 20, p. 2000.
23. Altgen, M.; Militz, H. Thermally modified Scots pine and Norway spruce wood as substrate for coating systems. *J. Coat. Technol. Res.* **2017**, *14*, 531–541. [CrossRef]
24. ASTM D2244. *Standard Practice for Calculation of Color Tolerances and Color Differences from Instrumentally Measured Color Coordinates*; UASTM International: West Conshochen, PA, USA, 2014.
25. ASTM D660. *Standard Test Method for Evaluating Degree of Checking of Exterior Paints*; UASTM International: West Conshochen, PA, USA, 2011.
26. ASTM D772. *Test Method for Evaluating Degree of Flaking (Scaling) of Exterior Paints*; UASTM International: West Conshochen, PA, USA, 2005.
27. ASTM D3274. *Test Method for Evaluating Degree of Surface Disfigurement of Paint Films by Fungal or Algal Growth, or Soil and Dirt Accumulation*; UASTM International: West Conshochen, PA, USA, 2017.
28. ASTM D662. *Standard Test Method for Evaluating Degree of Erosion of Exterior Paints*; UASTM International: West Conshochen, PA, USA, 2011.
29. Bazyar, B. Decay resistance and physical properties of oil heat treated aspen wood. *BioResources* **2012**, *7*, 696–702.
30. Rowell, R.M.; Ibach, R.E.; Nilsson, T. Wood durability and stability without toxicity. In *Sustainable Development in the Forest Products Industry: Chapter 8*; Universidade Fernando Pessoa: Porto, Portugal, 2010; pp. 181–208. ISBN 9789896430528.