Development and Characterisation of a Penetrating Barrier Treatment for Wood Protection

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Summary

Wood is a material commonly used for the construction of buildings and various facilities around the house. While its look and physical properties make it an appealing material, it is subject to be degraded by many agents, including water. Under the effect of water, wood can swell, warp, and crack. Impregnation of wood with water-proofing materials is a good way to reduce the effect of water on wood and add many years to its life expectancy. In this study, wood was impregnated with a formulation containing tertiary amine N-oxides to improve its dimensional stability. Because amine oxides can diffuse into the wood, no vacuum/pressure treatment was used. It was showed that this method could considerably reduce the swelling and shrinking of eastern white pine and white spruce when compared to untreated samples.

1. Introduction

Possessing great physical and mechanical properties for its quite low density, wood is an excellent building material. It also offers good insulation, possesses an appealing look, has a very low ecological footprint, and allows the sequestration of CO_2. However, it can also be damaged by various agents, like water and decay fungi (Hill, 2006). Water causes the wood to swell and shrink, following the ambient conditions (relative humidity and temperature) (Siau, 1995). The dimensional changes are not the same in every direction, being about twice as important in the tangential axis compared to the radial axis (Panshin *et al.*, 1964). The internal stresses thus produced into the wood will also eventually cause it to warp and crack. Decay fungi feed on the cell wall polymers, which decreases the chemical and physical properties of the wood and changes its appearance (Blanchette *et al.*, 1990; Reinprecht, 2016). While a good building design can contribute to prevent degradation, it is well-thought to also use a wood preservative treatment. Protecting the surface of the wood is cheap, easy, and can be done with different methods (coatings, surface modification, dipping, *etc.*). However, wood protected only near its surface will be prey to degradation as soon as it gets physically damaged, cracks, if the treatment leaches out or if the coating peels off. Consequently, it is a good practice to use an impregnation treatment to protect the wood in depth. Wood impregnation is usually performed *via* vacuum/pressure treatments (Freeman, 2008).

Many impregnation treatments exist to protect wood from water. The lumen of the wood cells can be blocked with compounds like oils, waxes, and resins (silane, amino, or phenol) (Kocaefe *et al.*, 2015; Reinprecht, 2016). However, while these products are effective to slow down the uptake of liquid water, they will not do much against air moisture and can not prevent dimensional changes. The hydroxyl groups (-OH) of the cell wall polymers can be modified or crosslinked with products like acetic anhydride (acetylation), formaldehyde, and epoxides (Reinprecht, 2016; Wang & Piao, 2010). These treatments greatly improve the dimensional stability of the treated wood, sometimes up to 70%, but they also increase its density (up to 20-22%). Wood can be protected from biodegradation through the impregnation of different biocides (triazoles, copper carbonates, borates, quaternary ammoniums, *etc.*) (Laks, 2008; Ross, 2008; Schultz & Nicholas, 2003).

Recently, an aqueous wood treatment called penetrating barrier was devised. It was described by Ross (2006) as a "dual phase system" including a Mobile phase which could easily penetrate the

wood and a Stationary phase which would stay near its surface. A good Mobile phase can be water soluble tertiary amine N-oxides, as they have the capacity to diffuse into the wood (Shen & Walker, 2001). When an amine oxide containing a long aliphatic chain is used, it can improve the dimensional stability of the treated wood (Tseng & Walker, 2000). They also possess antiseptic properties which prevents the damages from microorganisms like decay fungi. Furthermore, they promote the solubilisation of organic pesticides, like fungicides and insecticides, as well as their penetration into the wood, which increases the protection even further. Because the amine oxides can diffuse into the wood, the use of typical pressure treatments is not needed. However, the pH of the treatment solution must be monitored by using a buffer, preferably made of borates, to ensure the deepest penetration (Ross & Cutler, 2014).

In this study, a series of aqueous wood treatment solutions, which are expected to serve has the Mobile phase for a penetrating barrier, was developed using amine oxides, a borate buffer, and two organic fungicides commonly used in wood protection, propiconazole and 3-iodo-2-propynyl N-butylcarbamate (IPBC). Samples of eastern white pine (*Pinus strobus* L.) and white spruce (*Picea glauca* Moench (Voss)) were treated with various solutions and different diffusion times. They were subsequently tested for their improvement in dimensional stability.

The experiment used a factorial approach with the amine oxides, fungicides, and diffusion times as the factors. While the determination of the best combination was an important part of the project, the objectives of the study also included an understanding of the importance of each factor and their interactions on the performances of the treatment. Although biodegradation essays were also performed using brown-rot and white-rot fungi with satisfying results, this text will solely focus on the dimensional stability aspect of the treatment. The text is based on results published in Pepin *et al.* (2019).

2. Methodology

- **Samples preparation**

Boards from both species were brought to a moisture content (MC) around 12% in a conditioning room (20 ± 2 °C and 65 ± 5% RH) until constant mass and sawn into 20 x 20 x 20 mm cubes. The growth rings were aligned with an angle smaller than 10° to the tangential axis. All the samples were free of knot and visible stain.

- **Treatments**

For this study, two different amine oxides (AO) were used: dimethyldodecylamine N-oxide (DDAO) and dimethylhexadecylamine N-oxide (DHAO). They were combined in different ratios with a borate buffer and one or no fungicide to make the treatment solutions. The fungicide used were propiconazole and IPBC. Some solutions contained no amine oxide and buffer. To allow the diffusion, the wood samples have been placed in the conditioning chamber for 12 h, 24 h, or 48h. The combination of a treatment solution and a diffusion time represented a treatment. Details of the treatments are shown in Table 1.

Table 1. Conditions of the Different Treatments and Their ID

Amine Oxide	Fungicide	Diffusion Time	Treatment ID
No AO/buffer	No fungicide	12 h	0N12
		24 h	0N24
		48 h	0N48
	Propiconazole	12 h	0P12
		24 h	0P24
		48 h	0P48
	IPBC	12 h	0I12
		24 h	0I24
		48 h	0I48
DDAO + buffer	No fungicide	12 h	1N12
		24 h	1N24
		48 h	1N48
	Propiconazole	12 h	1P12
		24 h	1P24
		48 h	1P48
	IPBC	12 h	1II12
		24 h	1I24
		48 h	1I48
3 DDAO:1 DHAO + buffer	No fungicide	12 h	2N12
		24 h	2N24
		48 h	2N48
	Propiconazole	12 h	2P12
		24 h	2P24
		48 h	2P48
	IPBC	12 h	2I12
		24 h	2I24
		48 h	2I48
1 DDAO:3 DHAO + buffer	No fungicide	12 h	3N12
		24 h	3N24
		48 h	3N48
	Propiconazole	12 h	3P12
		24 h	3P24
		48 h	3P48
	IPBC	12 h	3I12
		24 h	3I24
		48 h	3I48

- **Treatment method**

The treatment solutions were brought to 65 °C under constant stirring and the samples were individually dipped for 15 s. They were then sealed in a plastic wrap for six hours to prevent the evaporation of the solution. After removal of the plastic wraps, the samples were set in a conditioning chamber (85 ± 1 °C and 85 ± 3% RH) for various periods to allow the diffusion of the products. The samples were then brought back to 12% before the tests.

- **Dimensional stability and equilibrium moisture content**

The dimensional stability of the samples was tested following two different methods: high relative humidity and immersion. In order to establish the gain in dimensional stability following the

treatment, treated and untreated samples were first oven-dried at 103 °C for 24 h to measure their dry radial (R_1) and tangential (T_1) dimensions. They were then either placed in a conditioning chamber (20 ± 1 °C, 95 ± 3% HR) for 90 h or immersed in de-ionized water (20 ± 2 °C) for 72 hours. Once equilibrium was reached, the samples were measured once more for their swollen (R_2 and T_2) dimensions. The swelling could be calculated with Eq. 1 to 3:

$$\alpha_R\ (\%) = [(R_2 - R_1)/R_1] \times 100 \quad (1)$$

$$\alpha_T\ (\%) = [(T_2 - T_1)/T_1] \times 100 \quad (2)$$

$$\alpha\ (\%) = \alpha_R + \alpha_T \quad (3)$$

where α_R, α_T, and α are the radial, tangential, and volumetric (total) swelling, respectively. The samples were then oven-dried again (103 °C for 24 h) and measured once more (R_3 and T_3) to calculate their shrinkage with Eqs. 4 to 6:

$$\beta_R\ (\%) = [(R_2 - R_3)/R_2] \times 100 \quad (4)$$

$$\beta_T\ (\%) = [(T_2 - T_3)/T_2] \times 100 \quad (5)$$

$$\beta\ (\%) = \beta_R + \beta_T \quad (6)$$

where β_R, β_T, and β are the radial, tangential, and volumetric (total) shrinkage, respectively. The improvement in dimensional stability was assessed as the anti-swelling and anti-shrinking efficiencies (ASE). They were calculated by comparing treated and untreated samples as:

$$ASE\ (\%) = [(\alpha_u - \alpha_t)/\alpha_t] \times 100 \quad (7)$$

$$ASE\ (\%) = [(\beta_u - \beta_t)/\beta_t] \times 100 \quad (8)$$

where α_u and α_t are the swelling of untreated and treated samples, while β_u and β_t are the shrinkage of untreated and treated samples.

During this test, for each method and wood specie, 10 samples were used for each treatment, along with 10 untreated samples. Three full cycles of swelling and shrinkage were performed to monitor the performances of the treatments over time.

The equilibrium moisture contents (EMC), as described by Hill (2006), is the moisture content wood will reach when placed in an environment where the conditions are fixed. It was studied for the samples submitted to high relative humidity and calculated with Eq. 9:

$$EMC\ (\%) = [(w_2 - w_1)/w_1] \times 100 \quad (9)$$

where w_1 and w_2 are the oven-dried mass and mass at equilibrium of the samples, respectively.

- **Sorption isotherm**

To further describe the high relative humidity test, sorption isotherms were traced with a VTI-SA+ vapor sorption analyzer (USA) from FPInnovations (Quebec city). In order to do this, oven-dried treated and untreated samples (5 mm x 5 mm x 5 mm) were exposed to increasing relative humidity levels (5%, 20%, 40%, 60%, 80%, and 95% ± 1%) to obtain an adsorption curve, followed by decreasing RH levels (80%, 60%, 40%, 20%, and 5% ± 1%) for the desorption curve, while the temperature was maintained at 25.0 °C ± 0.1 °C. For each level of RH, the EMC was determined when the mass of the samples changed less than 0.003% within 5 min.

- **Statistical analysis**

The statistical analysis was performed using a factorial design, where the analysis of variance (ANOVA) realized using the mixed procedure in the SAS University software (USA) at an α of 0.01.

3. Results and discussion

For a given specie, both methods, high relative humidity and immersion, gave quite similar results (Figs. 1 to 4). However, the values of anti-swelling/shrinking efficiency (ASE) obtained from the samples subjected to immersion were slightly lower, which was expected as this test is much harsher for the wood treatment. The statistical analysis showed that, for both species and methods, amine oxide (AO) was the only significant factor, with $p < 0.0001$. For the white spruce, the AO has a very clear effect on the dimensional stability. When using no AO, the values of ASE are nearly null or negative. When using AOs, the ASE rose quickly, becoming higher has the proportion of DHAO was increased. In the case of white pine, the ASE of samples treated without amine oxides was inexplicably high, competing with the best results obtained when using amine oxide. While it makes the interpretation of the results somewhat confusing, it is still very clear that the ASE of the samples treated with only DDAO is lower than those treated with DDAO and DHAO. It tends the prove that the length of the aliphatic chain of the amine oxides have an impact on the dimensional stability of the treated wood. Because time was not a significant factor, it can be hypothesised that a diffusion time shorter than 12 hours could be used without affecting the dimensional stability of the treated wood. However, it is possible that this change would affect other aspects of the treatment, like its resistance to leaching and depth of penetration.

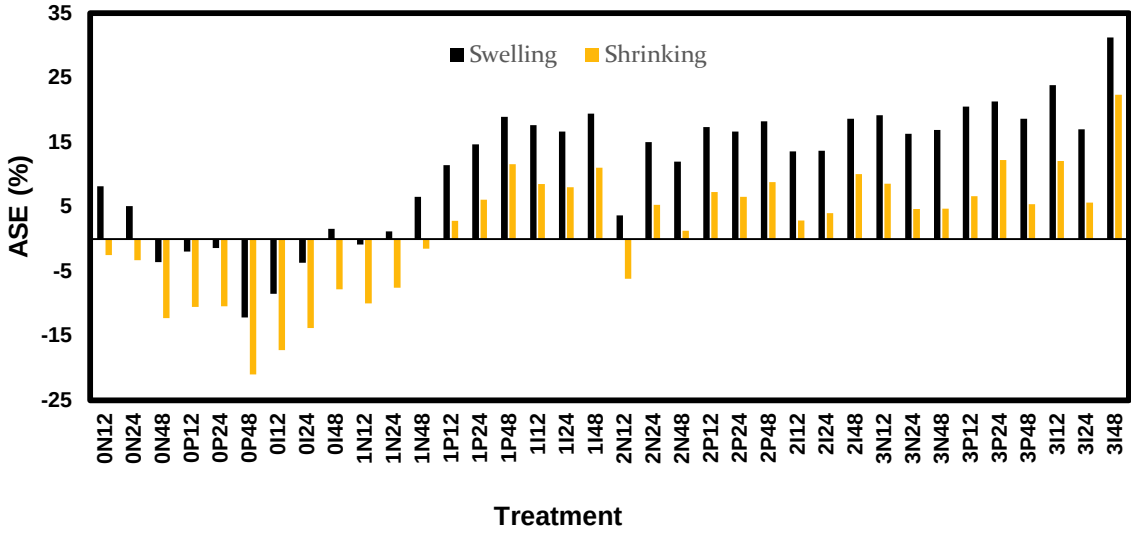

Figure 1. ASE values for the high RH test on the white spruce

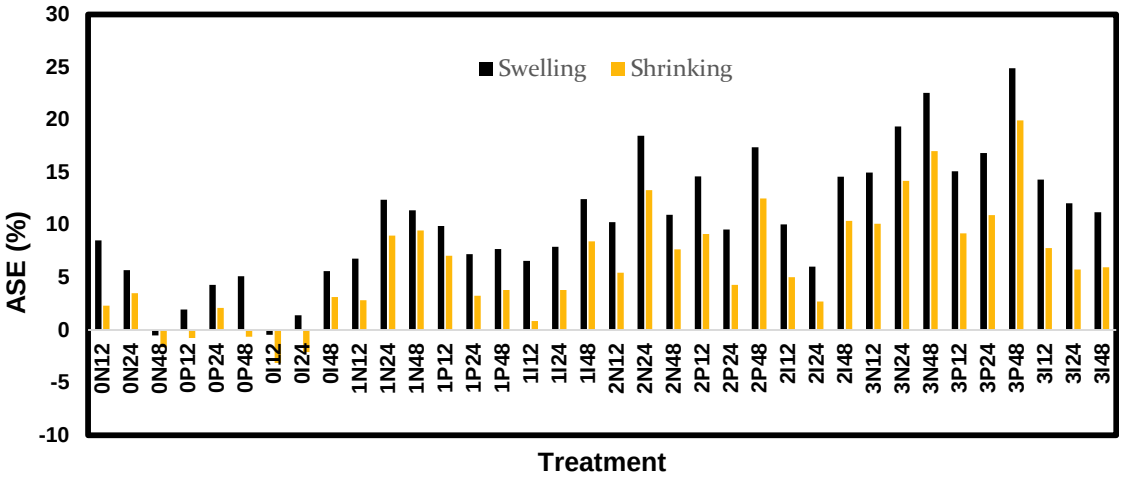

Figure 2. ASE values for the immersion test on the white spruce

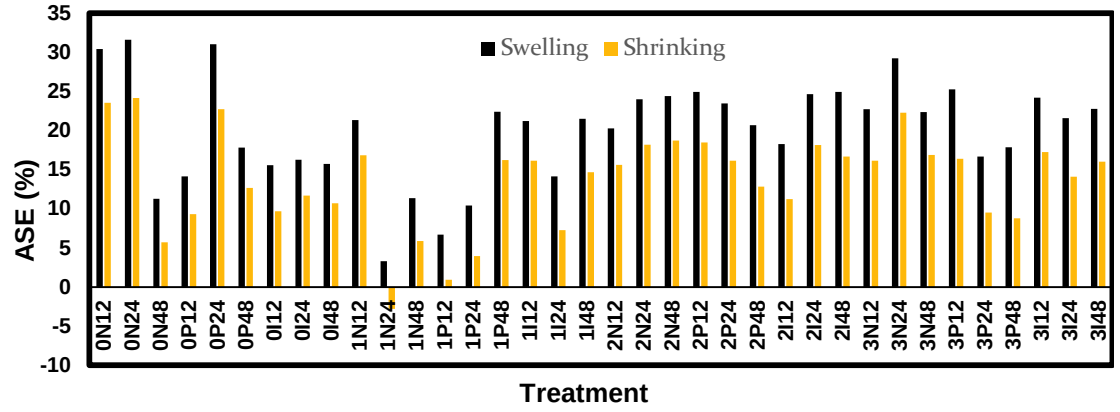

Figure 3. ASE values for the high RH test on the eastern white pine

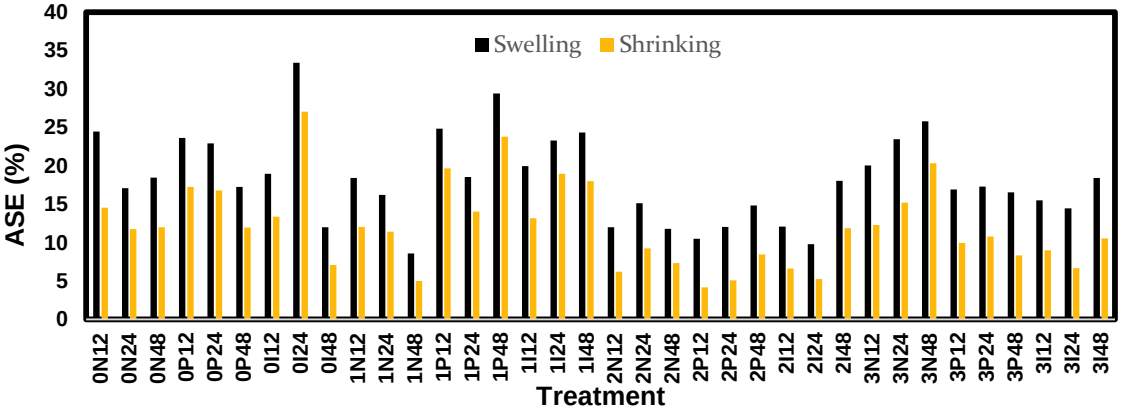

Figure 4. ASE values for the immersion test on the eastern white pine

When comparing the anti-swelling/shrinking efficiency (ASE) values during three full cycles, it is observed that they decreased from one cycle to another (Tables 2 and 3). It tends to indicate that the amine oxides leached out of the wood, leading to a loss of performances. However, this conclusion wouldn't make sense considering that even the samples treated without amine oxides were subject to this phenomenon. When taking a closer look to the dimensions of the treated samples, it is seen that they are roughly the same every cycle. On the other hand, when looking at the untreated samples, it is noticed that the dimensions of the oven-dried samples are quite larger every cycle. Consequently, if a shrinkage is smaller than the previous swelling, it will inevitably lead to a smaller subsequent swelling. Because the ASE is a comparison between treated and untreated samples (see Eqs. 7 and 8), it will be affected by the smaller dimensional changes of the untreated samples. Therefore, while it was more instinctive to conclude of a loss of performances, we can assume that it was the behavior of the untreated samples which lead to these smaller values of ASE rather than a problem with the treated ones.

Table 2. Anti-swelling and Anti-shrinking Efficiencies for the Three Successive Cycles of the High RH Test on the White Pine

Treatment	Anti-swelling Efficiency (%)			Anti-shrinking Efficiency (%)		
	1st Cycle	2nd Cycle	3rd Cycle	1st Cycle	2nd Cycle	3rd Cycle
0R12	30.4 (3.6)*	22.2 (4.3)	19.6 (4.2)	23.5 (4.0)	20.2 (4.1)	20.0 (4.1)
0R24	31.6 (3.6)	25.7 (3.7)	20.8 (4.2)	24.1 (3.3)	24.7 (3.6)	19.7 (4.2)
0R48	11.3 (4.8)	11.0 (4.1)	8.6 (3.9)	5.7 (5.0)	10.7 (4.0)	10.2 (2.7)
0P12	14.1 (4.5)	11.2 (3.4)	11.0 (2.9)	9.3 (4.3)	11.1 (3.3)	9.8 (3.1)
0P24	31.1 (3.6)	25.3 (4.3)	24.0 (4.4)	22.7 (4.2)	24.0 (4.2)	22.8 (4.3)
0P48	17.8 (4.2)	17.6 (3.6)	15.1 (4.4)	12.7 (4.3)	17.2 (3.6)	15.2 (4.1)
0I12	15.6 (6.1)	13.3 (5.9)	12.8 (5.7)	9.7 (6.4)	13.2 (5.7)	12.7 (5.5)
0I24	16.3 (5.0)	20.4 (4.3)	19.3 (4.2)	11.7 (5.1)	18.9 (4.1)	18.3 (4.2)
0I48	15.8 (4.9)	15.3 (4.5)	15.3 (4.1)	10.7 (5.0)	15.3 (4.3)	13.5 (4.1)
1R12	21.4 (3.2)	22.1 (3.3)	19.6 (3.2)	16.8 (3.4)	20.1 (3.2)	18.5 (3.4)
1R24	3.3 (5.3)	10.7 (3.5)	6.2 (4.3)	-2.8 (5.8)	8.9 (4.1)	4.7(3.3)
1R48	11.4 (5.2)	16.5 (2.7)	13.3 (2.9)	5.9 (5.3)	15.1 (2.6)	13.5 (2.8)
1P12	6.7 (4.5)	12.9 (3.0)	11.1 (3.1)	0.9 (4.5)	12.6 (2.9)	10.8 (3.2)
1P24	10.4 (2.3)	9.1 (2.0)	6.6 (1.7)	4.0 (2.3)	7.4 (2.0)	3.6 (1.9)
1P48	22.4 (0.9)	19.2(1.8)	17.4 (2.2)	16.2 (1.0)	18.0 (2.3)	15.5 (1.6)
1I12	21.2 (4.9)	18.4 (4.7)	16.7 (4.5)	16.2 (5.1)	16.5 (4.6)	15.3 (4.4)
1I24	14.2 (3.8)	11.4 (2.8)	9.5 (2.9)	7.3 (3.9)	9.8 (2.7)	7.8 (2.8)
1I48	21.5 (3.1)	21.2 (3.4)	19.4 (3.5)	14.7 (3.2)	19.4 (3.4)	18.1 (3.4)
2R12	20.3 (3.9)	17.5 (4.0)	14.1 (4.0)	15.6 (4.1)	15.5 (4.0)	13.6 (4.0)
2R24	24.0 (4.2)	19.7 (4.5)	17.5 (4.7)	18.2 (4.5)	18.2 (4.5)	16.3 (4.7)
2R48	24.4 (2.9)	20.6 (3.1)	18.3 (3.1)	18.7 (3.1)	18.6 (3.0)	17.6 (3.4)
2P12	24.9 (3.0)	20.5 (3.3)	17.2 (3.3)	18.5 (3.3)	18.0 (3.3)	16.1 (3.4)
2P24	23.5 (2.1)	19.1 (2.5)	15.9 (2.6)	16.1 (2.3)	16.7 (2.5)	15.1 (2.5)
2P48	20.7 (3.0)	15.4 (3.2)	12.7 (3.2)	12.8 (3.3)	13.4 (3.1)	10.3 (3.4)
2I12	18.3 (3.4)	11.8 (3.7)	11.1 (3.6)	11.2 (3.6)	9.2 (3.7)	9.1 (3.6)
2I24	24.6 (2.7)	19.2 (2.7)	18.5 (2.6)	18.2 (2.5)	16.6 (2.6)	18.1 (2.6)
2I48	25.0 (3.1)	17.3 (2.8)	16.7 (2.9)	16.7 (2.7)	15.0 (2.7)	15.8 (2.7)
3R12	22.7 (3.4)	17.9 (3.6)	14.5 (3.3)	16.1 (3.7)	15.0 (3.5)	13.4 (3.4)

Treatment	Anti-swelling Efficiency (%)			Anti-shrinking Efficiency (%)		
	1st Cycle	2nd Cycle	3rd Cycle	1st Cycle	2nd Cycle	3rd Cycle
3R24	29.3 (2.9)	24.7 (3.1)	22.8 (3.0)	22.3 (3.0)	22.5 (3.0)	22.0 (2.9)
3R48	22.4 (2.4)	19.0 (2.9)	14.9 (2.6)	16.9 (2.7)	15.2 (2.6)	13.6 (2.6)
3P12	25.3 (1.4)	18.8 (1.0)	16.0 (1.3)	16.4 (1.0)	16.3 (1.1)	15.9 (1.3)
3P24	16.7 (3.1)	11.5 (3.5)	9.0 (3.8)	9.5 (3.5)	9.3 (3.5)	7.7 (3.6)
3P48	17.9 (2.4)	11.8 (2.3)	10.2 (2.5)	8.8 (2.2)	9.7 (2.3)	9.9 (2.5)
3I12	24.2 (3.0)	23.0 (2.1)	19.6 (2.4)	17.3 (3.1)	20.3 (2.2)	19.5 (2.4)
3I24	21.6 (3.4)	16.8 (4.1)	12.8 (4.3)	14.1 (3.9)	14.0 (4.2)	11.8 (4.2)
3I48	22.8 (2.7)	17.9 (3.0)	14.8 (3.1)	16.0 (3.1)	15.2 (3.1)	15.4 (3.1)
*Values in parentheses represent the standard error of the result						

Table 3. Anti-swelling and Anti-shrinking Efficiencies for the Three Successive Cycles of the High RH Test on the White Spruce

Treatment	Anti-swelling Efficiency (%)			Anti-shrinking Efficiency (%)		
	1st Cycle	2nd Cycle	3rd Cycle	1st Cycle	2nd Cycle	3rd Cycle
0R12	8.1 (1.9)*	1.5 (3.8)	-5.6 (2.2)	-2.5 (1.9)	0.8 (3.8)	-5.1 (2.2)
0R24	5.1 (2.7)	2.5 (4.2)	-3.5 (2.7)	-3.3 (3.0)	1.6 (4.1)	-1.0 (2.5)
0R48	-3.6 (3.7)	-8.4 (2.6)	-8.9 (2.2)	-12.3 (3.8)	-7.9 (2.4)	-7.4 (2.0)
0P12	-1.9 (2.6)	-2.4 (2.6)	-3.3 (2.7)	-10.5 (2.7)	-2.6 (2.5)	-2.3 (2.5)
0P24	-1.4 (2.4)	-1.3 (2.2)	-1.7 (2.0)	-10.4 (2.3)	-1.5 (2.1)	0.2 (1.9)
0P48	-12.1 (2.2)	-5.5 (2.9)	-4.1 (3.0)	-21.0 (2.4)	-4.2 (2.8)	-4.5 (2.7)
0I12	-8.5 (3.3)	-5.9 (2.8)	-1.8 (4.5)	-17.2 (3.4)	-5.4 (2.7)	-1.6 (4.2)
0I24	-3.7 (2.6)	-0.9 (2.1)	-0.2 (2.2)	-13.8 (2.8)	-0.3 (2.1)	0.9 (2.1)
0I48	1.6 (2.0)	0.5 (1.1)	1.6 (1.4)	-7.8 (2.1)	1.0 (1.1)	0.9 (1.3)
1R12	-0.9 (3.2)	8.3 (2.2)	6.2 (2.1)	-10.0 (3.5)	7.0 (2.1)	7.0 (2.2)
1R24	1.2 (2.6)	5.8 (2.4)	4.5 (2.3)	-7.6 (2.6)	4.7 (2.2)	6.8 (2.2)
1R48	6.5 (2.7)	13.3 (1.9)	12.3 (1.9)	-1.5 (2.9)	12.6 (1.9)	12.6 (2.0)
1P12	11.5 (2.3)	9.3 (2.1)	8.9 (2.2)	2.8 (2.6)	8.4 (2.0)	7.9 (2.2)
1P24	14.7 (2.5)	10.7 (2.9)	11.0 (2.6)	6.1 (2.8)	10.4 (2.7)	10.4 (2.6)
1P48	18.9 (4.1)	16.5 (3.5)	17.1 (3.5)	11.6 (4.5)	16.2 (3.4)	14.5 (3.3)
1I12	17.6 (1.7)	9.5 (1.7)	10.3 (1.6)	8.5 (1.8)	8.7 (1.6)	8.3 (1.6)
1I24	16.6 (3.4)	8.0 (3.8)	8.6 (3.5)	8.0 (3.7)	7.6 (3.6)	9.1 (3.5)
1I48	19.4 (2.4)	12.7 (2.3)	12.8 (2.4)	11.0 (2.6)	12.5 (2.2)	11.2 (2.3)
2R12	3.6 (2.8)	1.1 (2.0)	1.1 (2.0)	-6.2 (2.8)	0.3 (1.8)	-0.7 (2.3)
2R24	15.0 (2.8)	8.9 (3.1)	8.4 (3.3)	5.3 (3.1)	8.0 (3.0)	8.9 (3.2)
2R48	12.0 (2.6)	6.4 (3.1)	5.6 (3.0)	1.3 (3.2)	5.9 (3.0)	5.5 (2.9)
2P12	17.3 (3.5)	9.5 (3.9)	8.8 (3.9)	7.3 (3.9)	9.0 (3.9)	9.7 (3.8)
2P24	16.6 (1.3)	8.4 (1.5)	8.3 (1.5)	6.6 (1.5)	8.2 (1.5)	8.2 (1.3)
2P48	18.2 (1.7)	10.7 (1.9)	10.5 (1.7)	8.8 (1.7)	10.2 (1.8)	11.7 (1.7)
2I12	13.6 (2.9)	4.2 (3.0)	6.9 (2.9)	2.9 (3.0)	4.0 (2.8)	7.4 (2.9)
2I24	13.7 (3.5)	6.0 (4.0)	7.2 (3.9)	4.0 (4.0)	5.4 (4.0)	7.1(3.7)
2I48	18.6 (3.7)	11.8 (4.2)	13.4 (3.9)	10.0 (3.9)	10.1 (4.1)	14.3 (3.6)
3R12	19.2 (5.0)	11.1 (5.7)	12.2 (5.5)	8.6 (5.7)	11.0 (5.6)	11.6 (5.4)
3R24	16.3 (2.2)	7.4 (2.2)	7.1 (2.3)	4.6 (2.3)	6.4 (2.2)	7.0 (2.3)

Treatment	Anti-swelling Efficiency (%)			Anti-shrinking Efficiency (%)		
	1st Cycle	2nd Cycle	3rd Cycle	1st Cycle	2nd Cycle	3rd Cycle
3R48	16.9 (1.8)	8.4 (1.7)	7.5 (1.7)	4.7 (1.9)	6.9 (1.8)	7.4 (1.7)
3P12	20.5 (4.9)	11.1 (5.3)	10.5 (5.2)	6.6 (5.5)	10.1 (5.3)	9.9 (5.2)
3P24	21.3 (4.5)	17.8 (4.8)	16.1 (4.9)	12.2 (5.0)	16.0 (4.7)	16.8 (4.8)
3P48	18.6 (3.5)	10.0 (3.0)	9.1 (3.1)	5.4 (3.3)	8.4 (3.1)	8.9 (3.1)
3I12	23.9 (5.9)	11.9 (5.9)	12.9 (5.8)	12.1 (7.3)	11.8 (5.8)	11.1 (5.6)
3I24	17.0 (3.9)	7.8 (4.3)	8.3 (4.3)	5.6 (4.4)	7.4 (4.2)	8.5 (4.2)
3I48	31.2 (6.4)	24.7 (7.0)	24.6 (7.1)	22.3 (7.1)	23.6 (7.0)	23.7 (7.0)
*Values in parentheses represent the standard error of the result						

The statistical analysis of the equilibrium moisture content (EMC) surprisingly showed no factor to be significant ($p < 0.01$) for both species. It would indicate that, even if the wood treated with amine oxides is quite more dimensionally stable, the amount of moisture it adsorbs is not affected (Figs. 5 and 6). Even more surprising, the sorption isotherm showed that the treated samples would adsorb moisture faster than the untreated ones and would finish at a higher moisture content (MC)(Fig. 7). An explanation for this might be the capacity of the amine oxides to make hydrogen bounds with up to eight water molecules (Kocherbitov *et al.*, 2007). Their presence in the treated samples adds the possibility to bind many water molecules inside, thereby increasing their EMC. However, only water bound to the cell wall polymers can induce dimensional changes (Rowell, 2014). Thus, while the EMC of both treated and untreated samples are not significantly different, it is plausible that the amount of moisture actually bound to the cell wall polymers would be reduced by the presence of amine oxides.

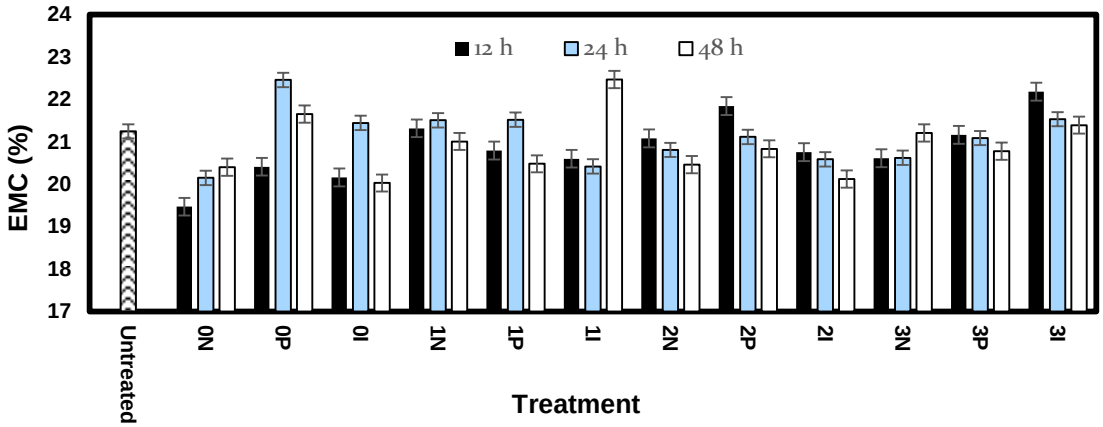

Figure 5. EMC of the eastern white pine samples during the first cycle of the high RH test

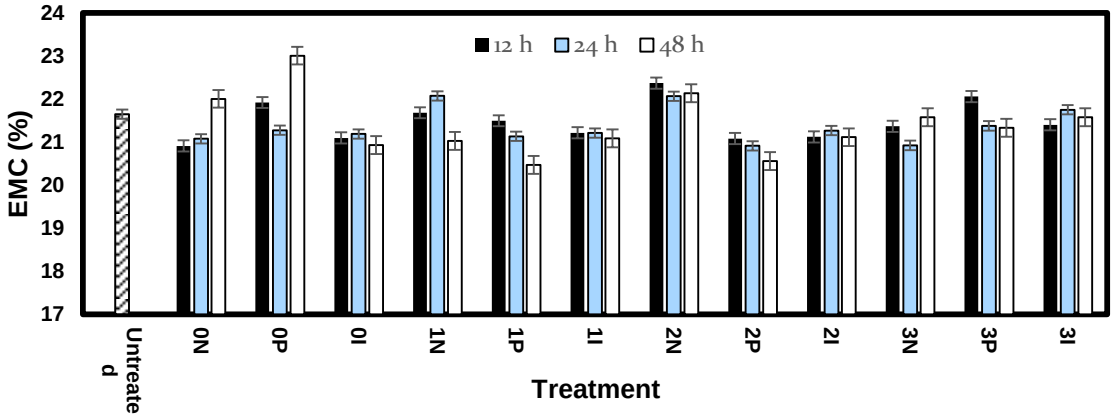

Figure 6. EMC of the white spruce samples during the first cycle of the high RH test

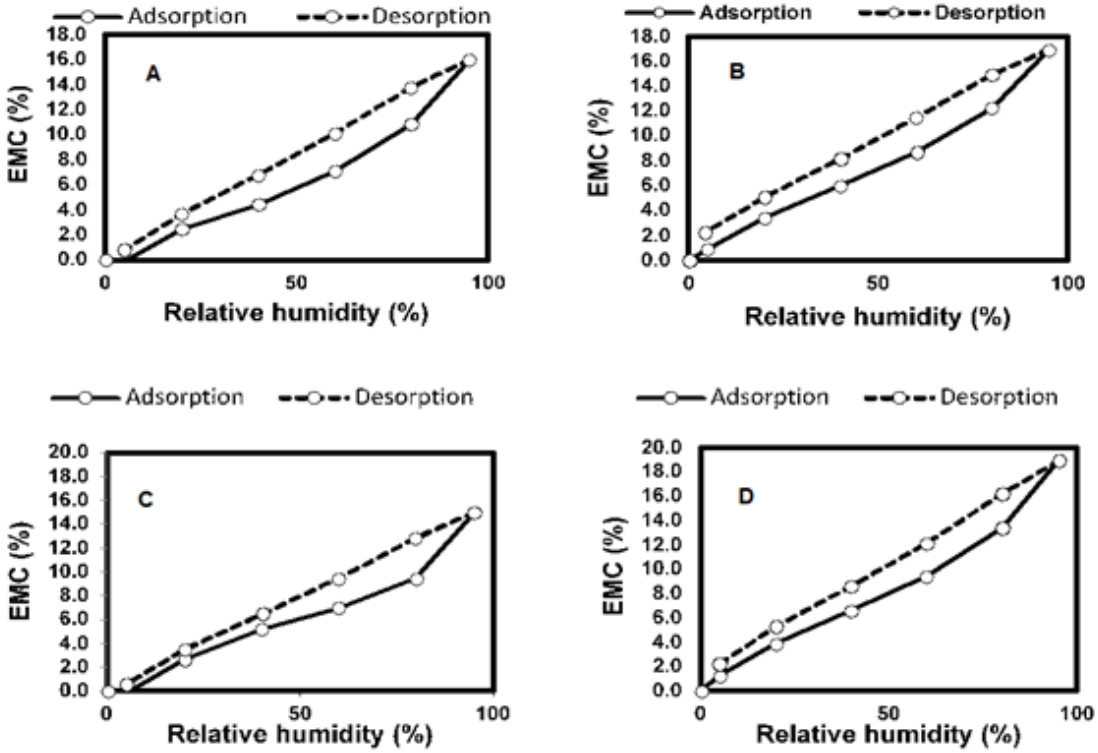

Figure 7. Sorption isotherms for the (A) untreated eastern white pine, (B) treated eastern white pine, (C) untreated white spruce, and (D) treated white spruce

4. Conclusion

The impregnation of eastern white pine and white spruce with amine oxides, through diffusion instead of vacuum/pressure treatments, proved to be a good way to improve their dimensional stability. Both methods tested, high relative humidity and immersion, gave quite satisfactory results, although the samples submitted to immersion were slightly less dimensionally stable. While the treatment didn't seem to affect the moisture intake of the treated wood, it is reasonable to believe that a portion of the water is actually bound to the amine oxides instead of the cell wall

polymers. The treatment seemed to keep its performances when performing three consecutive cycles, even though the ASE values decreased from one cycle to the other. This abnormality was due more to the behavior of the untreated sample having less dimensional changes over time than the treated samples having more dimensional changes.

While the other factors studied, the fungicides and diffusion times, did not seem to affect this aspect of the wood durability, they might affect other aspects like the depth of impregnation and the resistance to leaching, which will be the subject of future trials. The adding of a Stationary phase to the present solutions to make a complete penetrating barrier treatment is also intended to be done soon.

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