Improving Impregnation and Penetration Properties of Refractory Woods Through Cryogenic Treatment

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Cryogenic treatment *via* liquid nitrogen (LN) was evaluated as a means to improve the capability of impregnation and penetration in fir and spruce wood. There are a few vital problems that occur during the impregnation process of wood protection. One problem is that refractory woods have different anatomical features that make the impregnation process difficult. For the specimens that were conditioned with the air and oven, the retention changes were determined with an image analysis, scanning electron microscopy (SEM), and energy dispersive X-ray analysis (EDX). In addition, the density and equilibrium moisture content (EMC) values were measured. The LN treatment resulted in degradation in the bordered pits. Then, the margo and torus bonds were torn, the bordered pits were opened, and the liquid transportation of wood was facilitated. It was determined that the LN treatment and impregnation increased the depth and dispersion capability of the penetration. The LN treatment helped facilitate the flows from pores to pores by hindering the aspirations of the bordered pits, and thus the flow of chemicals was facilitated. Obtaining deeper penetration in refractory wood species will result in an improved impregnation process.

Keywords: Cryogenics; Liquid Nitrogen; Refractory wood; Bordered pit; Impregnation; Penetration; Permeability; Tanalith-E

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INTRODUCTION

Wood has a number of advantageous properties such as good strength-to-weight ratio, natural degradability, and warm aesthetic appearances that make it an environmentally sustainable material (Rowell 2005). The lifetime of a wood product is mainly determined by the environmental conditions that they are exposed to and the specific wood properties they possess (Lehringer *et al.* 2009; Bergman *et al.* 2010). Due to its non-homogenous structure, many drawbacks can be observed during experimentation. Meanwhile, wood is decomposed by a variety of biological agents, including fungi, bacteria, and insects (Durmaz *et al.* 2015). If the wood material is not preserved, the wood can easily be damaged relative to fungal stains, insect infestation, humidity, fire, *etc*., and such problems may limit the range of its feasible applications (Uysal and Yorur 2013). As a common preservation method, impregnation can extend wood's material life. Many preservative chemical solutions are being investigated to improve their effects and impregnation methods in implementations (Yorur *et al.* 2014).

Impregnation is a penetrative process of chemicals into wood materials (Sheard 1998). However, there are some vital problems that occur during the impregnation process in the wood protection. One such problem that occurs in refractory wood species is that their anatomical features make the impregnation process difficult (Dashti *et al.* 2012;

Yildiz *et al.* 2012; Durmaz *et al.* 2015; Ramezanpour *et al.* 2015). The application of substances that are used to enhance selected wood properties requires a movement of liquids into the wood at different depth levels (Flynn 1995). Therefore, a complete and homogenous penetration of liquid modified substances at the required depth of the wood material should be the intention (Lehringer *et al.* 2009). Several factors, such as the sapwood, heartwood, density, tracheids, resin canals, and bordered pits, are reported to influence the permeability of wood (Flynn 1995; Durmaz *et al.* 2015). The main role of the permeation of impregnation substances into wood material is attributed to the bordered pits (Wardrop and Davies 1961), which also affect the drying and impregnation capabilities of wood. These bordered pits serve as a main transfer path for the liquids from one cell lumen to another cell lumen (Siau 1995). They show diversity in shapes, numbers, sizes, and transit membranes based on cell types (Wiedenhoeft and Miller 2005; Erdin and Bozkurt 2013).

Fir and spruce wood that have refractory characteristics possess lower permeability due to the occurrence of pit aspiration during drying and impregnation (Bozkurt and Erdin 2011; Dashti *et al.* 2012). One of the important anatomical features influencing preservative uptake is the size and number of the cross-field pits (Usta and Hale 2003). Relatively small cross-field size of the pits and uniserial ray structure in these species influence the liquid permeability. The tracheids of fir and spruce woods have thin walls and wide lumens because they are a solid wood. The tangential diameter of a tracheid is approximately 20 µm to 65 µm, and its length is approximately 1300 µm to 4600 µm. In addition, the pores on radial cell wall can be observed as being single or double array. The impregnation capability for dry substances are difficult (Erdin and Bozkurt 2013). Because fir and spruce wood have low wood permeability (refractory character), a wood impregnation process with preservatives can encounter problems (Bozkurt and Erdin 2011). Different methods have been tested to improve the impregnation properties of such wood species (Ramezanpour *et al.* 2015). Being a material property, permeability has a specific importance in preservative impregnation and wood drying processes (Lehringer *et al.* 2009). Several methods have been implemented to improve liquid permeability. Among these methods, vacuum and pressure impregnation methods generally provide the best results in industrial implementations (Lehringer *et al.* 2009). In such methods, a more homogenous distribution, deeper penetration, and higher absorption of the applied substance can be obtained (Bozkurt and Erdin 2011). Alternative studies are still required due to the difficulties encountered in the impregnation process to increase the capability of impregnation.

Studies about impregnation have concentrated on permeability, impregnation, and liquid nitrogen treatment. The studies on permeability have stressed the various treatments associated with the pit torus position (Bao *et al.* 2001), mesopores and micropores in the wood cell (Yin *et al.* 2015), use of bioincising to enhance permeability (Lehringer *et al.* 2009), enhancement of the liquid permeability of Chinese fir (He *et al.* 2014), increase in permeability by enzymatic treatment (Durmaz *et al.* 2015), and the retention and penetration evaluation with Tanalith-E preservative (Yildiz 2007). The studies about impregnation have concentrated on the improvement of the impregnability of refractory spruce wood (Yildiz *et al.* 2012), improvement of impregnation by microwave radiation pretreatment of wood (Ramezanpour *et al.* 2015), effect of impregnation on wood mechanics (Villasante-Plágaro *et al.* 2013), impregnation of laser-incised wood with Tanalith (Islam *et al.* 2014), and the effect of moisture content and temperature on the mechanical properties of wood (Gerhards 1979). In contrast, the effects of liquid nitrogen have been investigated by many researchers. Kollmann (1940) evaluated the mechanical properties for temperatures between -190 °C and 200 °C and found that the modulus of rupture of a wooden baseball bat increased 26% after it was treated at -190 °C for 24 h (Kendra and Cortez 2010), combustion properties of wood material treated with liquid nitrogen (Çalım 2013), effect of liquid nitrogen on modulus of elasticity of wood (Zhao *et al.* 2015). As seen above, the studies have not considered the influence of liquid nitrogen on the impregnation, penetration, and border pit of the wood. In this paper, the implementation of liquid nitrogen was investigated to improve the capability of impregnation and penetration in fir and spruce wood. As is well known, liquid nitrogen of -196 °C is widely preferred in cryogenic applications. When green wood is cooled below the freezing point, ice forms in the cell lumens, which makes the cell walls shrink as the expanding of the ice lens in the lumen occurs (Zhao *et al.* 2015). Therefore, pretreatment of wood with liquid nitrogen (LN) could be a promising technique in this field and would apply a different method. Obtaining deeper penetration in refractory wood species will result in an improvement in the impregnation and drying process.

EXPERIMENTAL

Materials

Vital problems can occur during the wood protection process. These are mainly related to refractory wood species that have difficulties during the impregnation process. Therefore, complete and homogenous penetration of liquid substances at the required depth of wood material should be the objective. In this study, the increasing retention of liquid nitrogen in refractory woods was studied. For this purpose, retention changes were determined with image analysis, scanning electron microscopy (SEM), and energy dispersive X-ray analysis (EDX). In addition, the density and equilibrium moisture content (EMC) values were measured.

Wood species

Uludag fir (*Abies nordmanniana* subsp. *Bornmuelleriana* Mattf.) and Oriental spruce (*Picea orientalis* L.) were chosen randomly from a 35-year-old plantation (Hacioglu Ltd., Karabuk, Turkey). There was a special emphasis on the selection of wood materials that were non-deficient, whole, knotless, normally grown without zone-line, reaction wood, decay, insect infection, and fungal infection. The selected wood materials had 2 to 4 rings per 10 mm. In experiment, approximately 2 m^3 of wood was used in total.

Impregnation material

The chemical Tanalith-E 3492 with a concentration of 3% was used as an impregnation chemical (Hemel Emp. San. and Tic. A.Ş, Istanbul, Turkiye). Tanalith-E is a copper-containing wood preservative with density of 1.3 $g.cm^{-3}$.

Liquid nitrogen

As nitrogen is inert to most materials and is safe in both freezer and cooler, 750 L peculiarities of liquid nitrogen (Kardemir A.Ş., Karabuk, Turkiye) with a density of 8.08^{-1} $g.cm^{-3}$, boiling point of -197 °C, and melting point of -210 °C were used.

Preparation of experimental samples

The specimens were kept in a room at 20 °C ± 2 °C and 65% ± 3% relative moisture until their weights became stable. The lumber specimens with a size of 50 mm × 200 mm × 900 mm (radial, tangential, and longitudinal direction) were cut from fir and spruce for impregnation. Ten samples were prepared from each group for impregnation treatment. Then, end grain sections of the samples were sealed with acrylic-copolymer resin based waterproof membrane. The samples, except for the non-treated ones, were kept under liquid nitrogen medium for 15 min. After the liquid nitrogen treatment, the specimens were kept in a sunless atmospheric medium for 7 d. Then, the specimens were impregnated with Tanalith-E, using a pressure-vacuum impregnation method. In implementation, pre-vacuum of 600 mm-Hg was firstly applied for 15 min. After that impregnation chamber was filled with Tanalith-E, and a pressure of 2 bar was applied for 60 min. After unloading the impregnation solution, a final vacuum was applied. All of the specimens were weighed at each stage before and after LN treatment and the impregnation. The specimens were kept in a sunless atmospheric medium for 7 d, after impregnation. Retention was calculated by the equations indicated in ASTM D 1413 (2016),

$$\mathrm{R} = \frac{G.C}{\mathrm{V}} \times 10 \tag{1}$$

$$G = M_2 - M_1 \tag{2}$$

where R is the retention (kg.m^{-3}), G is the amount of preservative solution absorbed by the sample (kg), C is the concentration of the impregnating material solution (%), and V is the specimen volume (m^3).

Methods

Density, porosity, and equilibrium moisture content

Twenty specimens used for each test. Air dry and oven dry densities were determined in accordance with ISO 3131 (1975). Samples were kept at 20 °C ± 2 °C with a relative moisture of 65% ± 5% in a conditioning container. The oven-dried properties were determined after drying the samples at 103 °C ± 2 °C in a drying oven until the weights of the samples were stabilized. The EMC was determined in accordance with ISO 3130 (1975). Porosity of the samples was calculated according to the equation given below (Bozkurt and Erdin, 2011).

$$\text{Porosity (\%)} = \frac{oven\ dried\ density}{1.5} \times 100 \tag{3}$$

Image analysis

The impregnation area on the cross-section was measured by a vision builder for automated inspections (VBAI; National Instrument, 5.1, New York, USA). It was used as a program tool for acquiring and analyzing the images. A sample result and the measurement of RGB values for the surface based on VBAI is given in Fig. 1.

SEM analysis

Fir and spruce wood specimens were cut at the size of 5 mm in radial direction, 5 mm in tangential direction, and 3 mm in longitudinal direction for the experimental processes of without treatment, impregnation, liquid nitridation, and liquid nitrogen-impregnated in the oven-dried and air-dried applications. All experimental specimens were kept in a room at 20 °C ± 2 °C with a relative moisture of 65% ± 3% until their weights became stable. The SEM studies were conducted to analyze the effect of the pretreatment of liquid nitrogen and impregnation on the structure of cell walls and bordered-pit (including torus, porous, margo). Ultra-structural observations were operated at 15 Kv using a Hitachi 4500 FE-SEM (Zeiss, Munich, Germany). The specimens prior to the investigation were coated with gold. The microstructures of the oven- and air-dried specimens without treatment, impregnation, liquid nitrogen, and liquid nitrogen-impregnated were investigated.

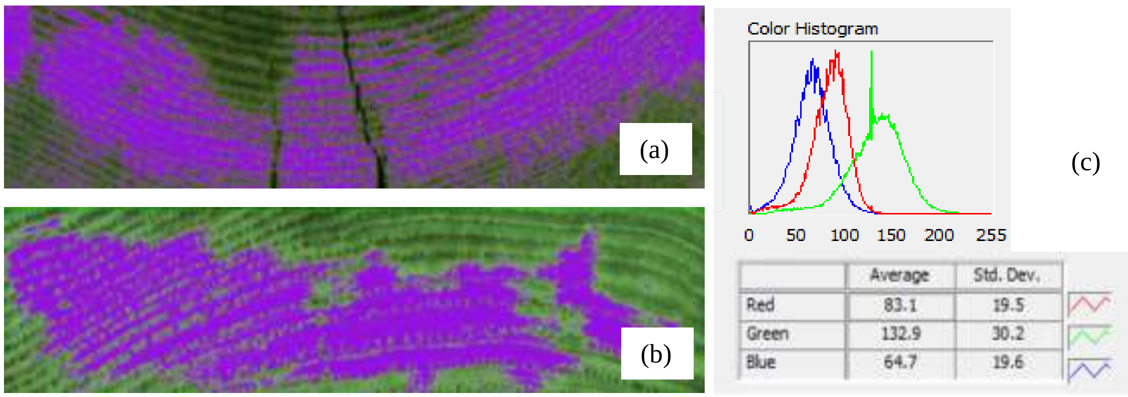

Fig. 1. An application of the measurement of RGB values based on VBAI for a cross-section of oven-dried fir (a), air-dried fir (b), and their RGB scales (c)

EDX analysis

Energy dispersive X-ray is a non-destructive X-ray technique used to identify the elemental composition of materials. Specimens with the size of 30 mm × 30 mm ×10 mm were cut from fir and spruce woods. The chemical compositional point and map analyses were conducted for retention in ppm by EDX detector (Zeiss, Munich, Germany) for all specimens.

RESULTS AND DISCUSSION

The main objective of this study was to examine the effect of LN on the wood species determined. The major findings obtained are explained in detail with respect to density, EMC, retention, image analysis, Field Emission-SEM, and EDX.

Density

Density is one of the main character traits for wood. The low density of a wood is mainly related to porosity, cell wall thickness, and the amount of extractive substance. The density and porosity ratio affect many factors such as impregnation, adhesion, and strength. The oven- and air-dried wood densities that were obtained after the variety of treatments are given in Table 1.

The density changes after LN treatment were measured for all wood specimens. The LN treated specimens' densities decreased approximately 0.2 g.cm^{-3} as compared to those that were not treated. According to Table 1, the decrease in density after LN treatment was explained by the extractive materials that were attached to tracheid cell wall being removed from the cell. The extractive materials were either penetrated completely or held superficially on the cell wall. Alternatively, they could be stored in the lumens. These materials decreased permeability and increased the densities. The extractive materials can be removed from the wood by using solvents such as water, cold water, and alcohol (Erdin *et al.* 2013).

Table 1. Densities of Fir and Spruce Wood

Densities of Wood (g/cm^3)									
	Porosity (%)	Oven-dried				Air-dried			
		Non-treated	LN	Imprg.	LN and Imprg.	Non-treated	LN	Imprg.	LN and Imprg.
Fir	74	0.39 (0.01)	0.37 (0.01)	0.40 (0.01)	0.41 (0.02)	0.43 (0.01)	0.41 (0.01)	0.44 (0.01)	0.45 (0.02)
Spruce	72	0.42 (0.01)	0.41 (0.01)	0.42 (0.01)	0.43 (0.01)	0.45 (0.02)	0.43 (0.01)	0.46 (0.01)	0.48 (0.01)
Note: The values shown in brackets give the standard deviations of the measurements									

Equilibrium Moisture Content

Wood is a hygroscopic material, and therefore it constantly exchanges moisture with ambient air (Engelund *et al.* 2013). This moisture change is an undesirable behavior for many wood applications such as joining, bounding, and coating. The moisture content of wood in equilibrium after variation treatment is shown in Table 2.

Table 2. Moisture Content of Wood in Equilibrium

Moisture Content of Wood in Equilibrium (%)							
	Oven-dried			Air-dried			
	LN	Imprg.	LN and Imprg.	Non-treated	LN	Imprg.	LN and Imprg.
Fir	10.4 (1.09)	11.2 (1.9)	10.8 (1.01)	10.5 (1.09)	10.2 (1.11)	13.2 (1.44)	11.9 (1.29)
Spruce	8.1 (1.02)	10.5 (0.85)	10.2 (1.54)	9.7 (1.12)	8.9 (1.21)	11.4 (1.06)	10.8 (0.86)
Note: The values shown in brackets give the standard deviations of the measurements							

The EMC values of the specimens were measured before the treatments. The air-dried EMC values were 10.5% for fir and 9.7% for spruce specimens. The LN treatment before impregnation positively influenced through lowering the EMC values of the wood specimens. The decrease in EMC value of spruce was higher than that of fir after the LN treatment. In contrast, the increase in EMC values after impregnation was a disadvantage for the wood. As shown in Table 2, the EMC values of the impregnated woods increased. The EMC values of the fir and spruce treated with LN and impregnation were determined to be lower in comparison to the impregnated specimens without LN treatment. This was due to the LN causing the changes in the border pit and chemical structure.

Retention

The accessibility of the treating reagent to the reactive chemical sites in wood is a big phenomenon. To increase accessibility to the reaction site, the chemical must penetrate the wood structure (Rowell 2005). The requirements of penetration and retention are both equally important in determining the quality of preservative treatment (Ibach 1999). The retention values obtained for fir and spruce are given in Table 3.

Table 3. Retention Values of Fir and Spruce Wood

Retention (kg.m^{-3})						
	Oven-dried			Air-dried		
	Non-treated	LN	Changes (%)	Non-treated	LN	Changes (%)
Fir	3.12 (0.54)	7.54 (0.52)	141.66	5.89 (0.24)	7.49 (0.60)	27.16
Spruce	1.39 (0.28)	2.83 (0.27)	103.59	1.63 (0.35)	2.48 (0.40)	52.14
Note: The values shown in brackets give the standard deviations of the measurements						

In the impregnation tests conducted with LN-treated specimens, an increase in the retention values were obtained in comparison to the non-treated specimens, as shown in Table 3. The retention values of the air-dried and LN-treated spruce specimens was 2.48 kg.m^{-3}. The specimens without LN treatment had the lowest retention values among all of the impregnated specimens. As shown in Table 3, the increase in the retention for oven-dried and air-dried impregnated fir were 141.7% and 27.2%, respectively. Similarly, the increase in retention for oven-dried and air-dried impregnated spruce were 103.6% and 52.1%, respectively. The retention values for oven-dried fir and spruce were higher. According to Erdin and Bozkurt (2013) impregnation of dried spruce is much more difficult than that of the wood which has higher MC. Retention values for both the LN treated air-dried and oven-dried samples were similar, so it can be said that the samples were impregnated as much as possible. The retention in the untreated air-dried samples had been higher than that of the oven-dried samples. Thus, the changes obtained in percent (see Table 3) in oven-dried samples were seen higher than that of air-dried samples. Similarly, Islam *et al.* (2009) explained that the higher moisture content might cause a lower penetrated area on the central surfaces of wood. Moreover, the higher the increase in retention, the better quality in penetration and protection.

The minimum penetration for refractory species is typically defined as 10 mm (AWPA 2003). An evaluation of the wood samples based on the AWPA minimum penetration standard are given in Fig. 2. Yildiz (2007) stated that in most cases, at least 80% of the boards sampled were required to meet or exceed this minimum. In addition, the relation between density and retention depends on the amount of impregnation chemicals absorbed by the wood. In this study, the reduction in the density after LN treatment and removal of the extractive materials helped facilitate an increase in retention values. This situation can be interpreted as the freezing and expanding of the water inside the wood *via* LN. When the water transforms the ice, its volume increases approximately 8.3%. The OH groups that are attached on the wood structure, cell walls, lumens, amorphous sites, border-pits, margo, and torus are expanded by the freezing effect that can either damage or break cell walls. The state of the LN treatment at bordered-pits is shown in Fig. 3b. In contrast, the timber that was dried by a higher temperature had certain advantages unlike freezing. The dried timber increases the permeability of the impregnation liquids and provides lower moisture content after impregnation (Terziev and Daniel 2002).

Image Analysis

The depths and dispersions of penetration of the specimens treated with LN and impregnation were measured by using an image analysis software and the cross-sectional images of the specimens as shown in Fig. 2. It was determined that the LN treatment and impregnation increased the capability and depth of penetration. It was observed that the impregnation materials penetrated well into the LN-treated and impregnated specimens where they were homogeneously distributed in every site of the cross-section of the specimens. The measurements of RGB values in the cross-section showed that the higher penetration percentage of impregnation materials was observed in the LN-treated specimens. The preservative penetration of the wood specimens was improved with the LN treatments and the improvement obtained was considerable for the samples. The retention values were in agreement with the data obtained by image processing software.

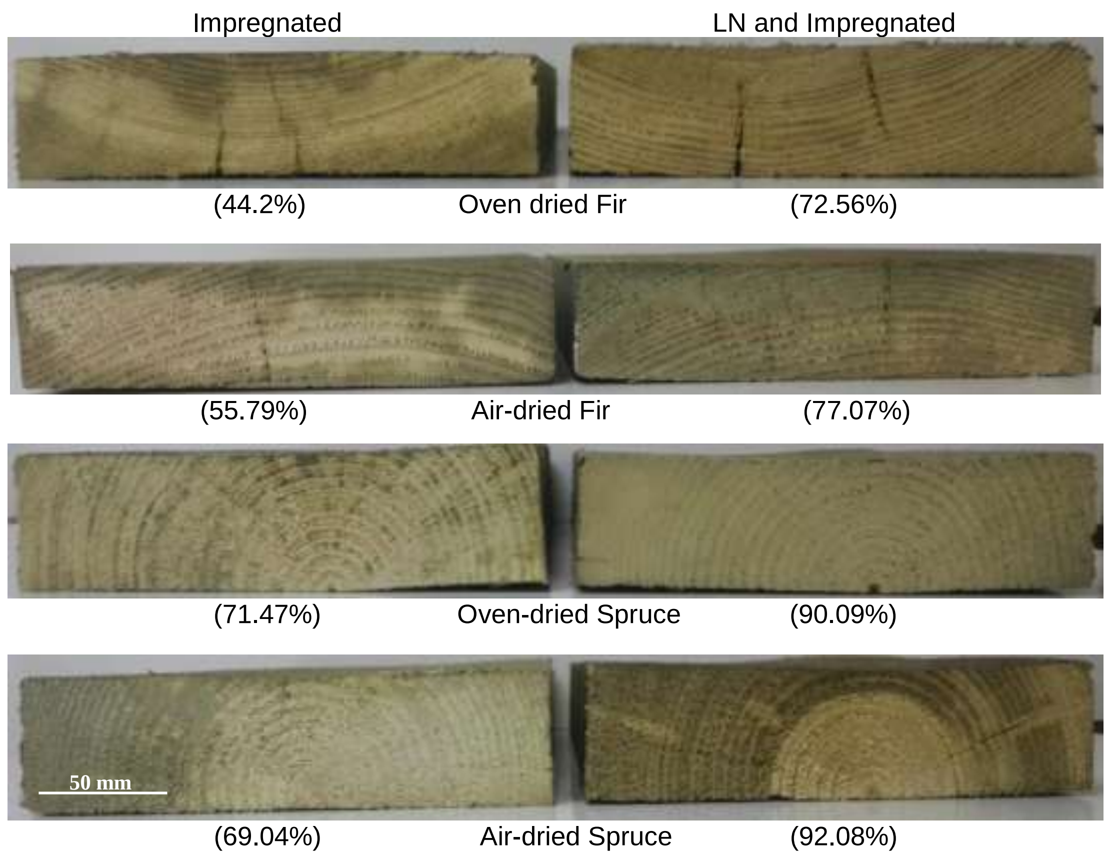

Fig. 2. Penetration percentage of fir and spruce after impregnation measured with image analysis: values shown in brackets give %RGB values for cross-sections; all images are of the same scale

SEM Analysis

The SEM studies were conducted to closely analyze the effect of LN treatment on the structure of cell walls. The SEM results clearly depicted the penetration and permeability of LN. As expected, the SEM results showed that the LN treatment increased the permeability by opening the border pits of the fir and spruce specimens as compared with the untreated ones. The SEM images of the air- and oven-dried untreated and LN-treated wood specimens are given in Fig. 3. Nearly all the pit membranes of the untreated specimens were aspirated, and therefore aspiration occurred (Figs. 3a, 3c, 3e, and 3g). In Figs. 3b, 3d, 3f, and 3h, almost all of the pit membranes of the LN-treated specimens were opened. This prevents aspiration due to the damaged bordered pits. In other words, the status of the bordered pit played a large role in whether it was open or closed.

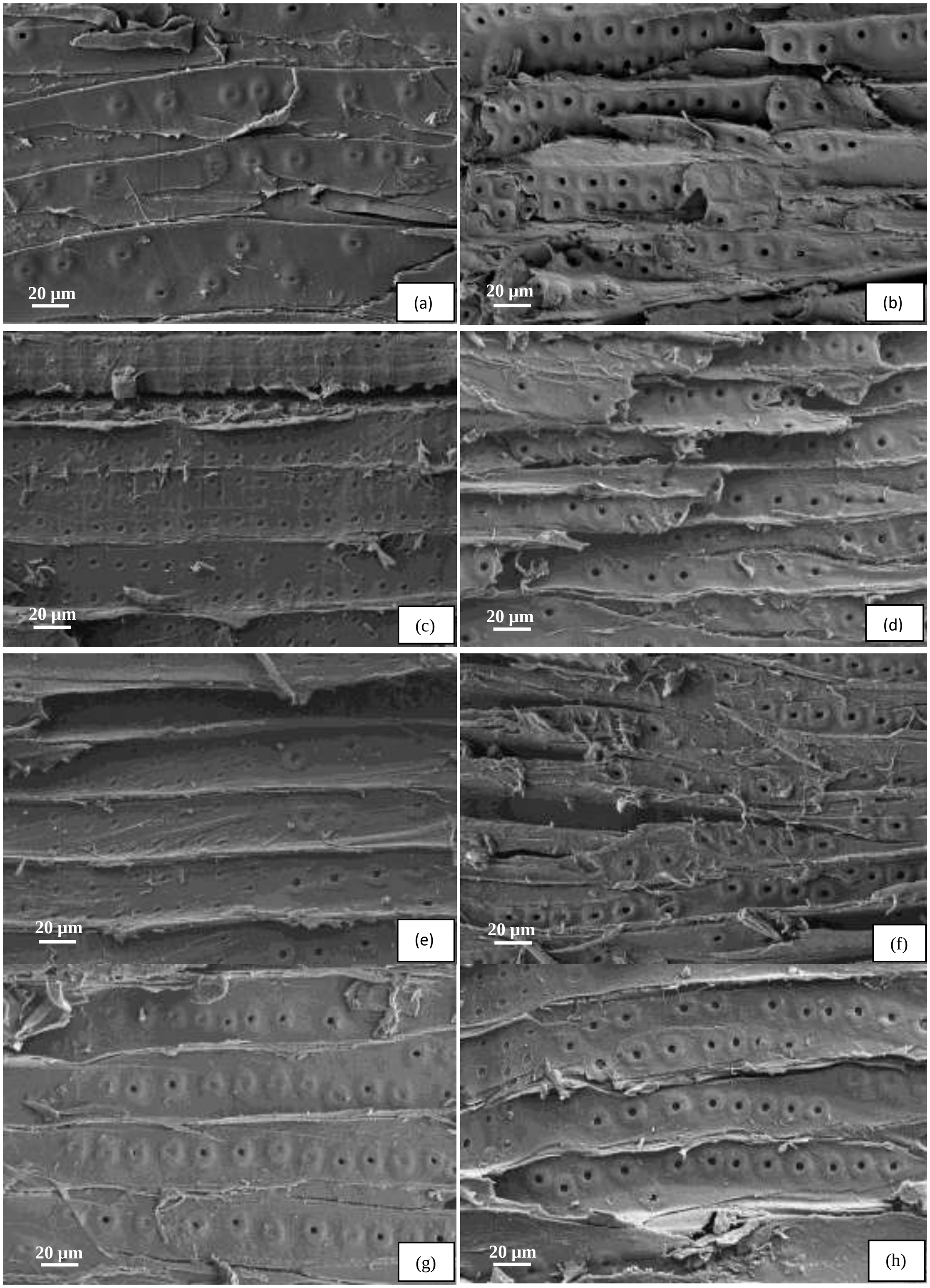

Fig. 3. SEM images of wood specimens (1000×) show the bordered pits: air-dried untreated Fir (a), air-dried and LN-treated Fir (b), oven-dried untreated Fir (c), oven-dried and LN-treated Fir (d), air-dried untreated Spruce (e), air-dried and LN-treated Spruce (f), oven-dried untreated Spruce (g), and oven-dried and LN-treated Spruce (h)

The LN treatment showed visible effects on the microstructure of wood. The LN treatment resulted in degradation in the bordered pits. Afterwards, the margo and torus bonds were torn, and the bordered pits were completely opened, as shown in Fig. 4. According to SEM analysis, this situation can be explained by LN treatments. Thus, LN treatment had a remarkable effect on bordered pit aspiration. When the LN-treated, untreated fir, and untreated spruce specimens were compared, it was observed that the number of bordered pits aspired at the radial walls in the LN-treated specimens were very limited in number.

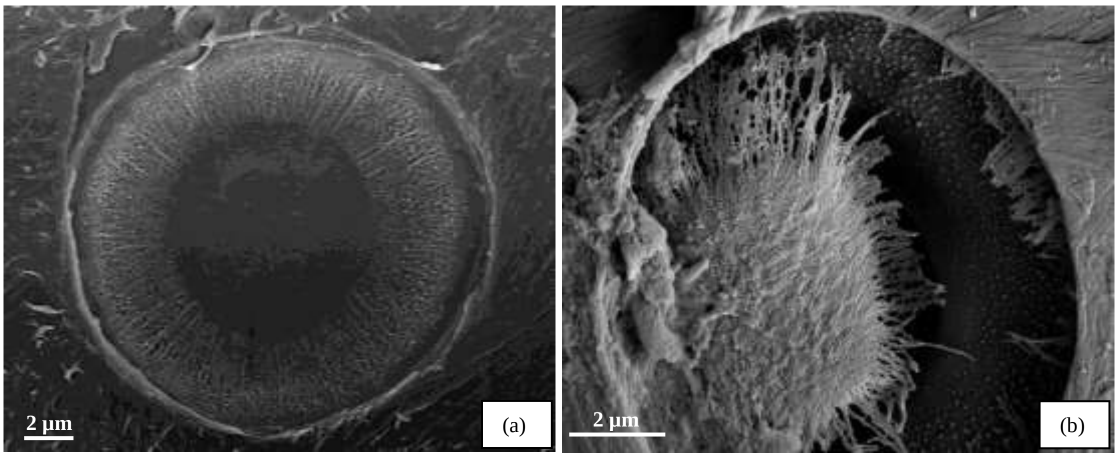

Fig. 4. Spruce wood margo and torus bonds in untreated specimen (a); LN-treated specimen (b)

As shown in Fig. 4b, the LN treatment damaged the cell walls and the structure of the tracheids. The breakage in the margo bond resulted in the torus becoming nonfunctioning. Numerous studies on margo and torus were conducted to increase permeability. Olsson *et al.* (2001) attributed the lower permeability in the pine heartwood to a high degree of aspiration in the bordered pits. In the studies about the enzymes, the closed bordered pits were aimed to be opened by the enzymatic treatment *via* destruction of the structure of the closed bordered pits, and thus the permeability increased (Durmaz *et al.* 2015). The amount of impregnation on the cross-section of wood increased due to microwave radiation (Ramezanpour *et al.* 2015). The aim of the microwave radiation processes was to increase the fluid movement capability at the tracheids and to create new zones at the bordered pits by destroying the torus and margo. Thus, new capillaries for liquid flow are provided at bordered pits. The penetration and permeability are important for the flow of liquid. Damage in the pit apertures can considerably facilitate the penetration of preservatives. He *et al.* (2014) also reported similar results about permeability improvement. After microwave treatment, the pit membranes were destroyed and the microstructural changes became prime factors that accounted for the permeability improvements.

EDX Analysis

The SEM-EDX studies revealed a higher deposition of copper in the cell wall and pit aperture of the LN-treated and impregnated woods. This was in agreement with the values of retention and image analysis. The impregnation material attached on bordered pits for the LN-treated air-dried spruce specimen were scanned by Fe-SEM and the selected points simultaneously were analyzed by EDX, as shown in Fig. 5.

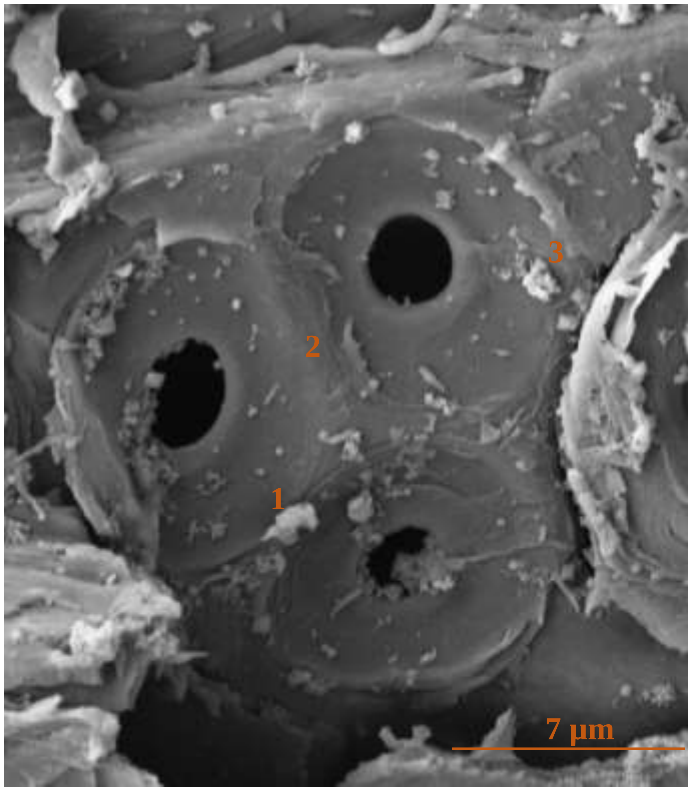

Fig. 5. The impregnation material attached on bordered pits for LN-treated air-dried spruce specimen

It was observed that the LN treatment partially prevented the working function of the torus and margo. Moreover, this was also supported by the data obtained by the retention amounts, image processing, and SEM. The LN treatment helped facilitate the flow from pores to pores by hindering the aspirations at the bordered pits, and thus the flow of chemicals was facilitated. The attachment of the impregnation material to the cell wall and bordered pits are very important, from the relation of wood material and moisture point of view. The dimensional stability of wood was considerably reduced after impregnation. These results showed that the LN treatment was more efficient and important to the cell wall. The results of the EDX analysis of the bordered pits of the air-dried spruce with LN treatment are given in Table 4.

Table 4. EDX Analysis of Spruce Wood (Air-dried) After Impregnation *via* LN Treatment

Mass Percentage (%) of LN-treated and Impregnated Spruce Wood					
Spectrum	C	N	O	Si	Cu
1	46.01	4.62	29.19	0.21	19.96
2	58.06	6.30	29.45	0.00	6.18
3	40.67	5.17	28.47	5.54	20.15
Untreated	48.83	0.20	50.72	-----	0.25

According to the results of the EDX analysis as shown in Table 4, the highest copper contents in the impregnation material were determined at Spectrum 1 and 3. The amount of copper was less in Spectrum 2. The nitrogen has held on the wood according to the EDX analysis. The nitrogen was measured as approximately 0.2% in the untreated specimens and 6.3% in the treated specimens. The effect of LN on the wood was interpreted where the oxygen and hydrogen in the wood were substituted by the nitrogen. The LN affected the behaviors of absorption and desorption in the wood. Thus, the LN dropped the EMC values in the wood.

CONCLUSIONS

1. The LN-treated fir and spruce specimens showed that the treatments resulted in a notable increase in the amount of penetration and retention values. The amount of retention changed depending on the wood species, due to their anatomical structure differences. The LN treatment decreased the density of the wood by subtracting the extractives. So, the LN treatment can also be used to remove the extractives.
2. The status of the bordered pit, whether it was open or closed, had great importance in wood preservation and drying. Many of the pit apertures in the LN-treated wood were torn. The LN treatment caused an increase in liquid transportation by affecting the cell structure. Thus, the preservative substance easily penetrated the wood.
3. The LN treatment can be alternatively employed in fields where higher retention values are required. It is a relatively low-cost method and easy to use in comparison to microwave implementations. High retentions in impregnation were achieved with LN treatment to improve the durability and service life of wood structures.

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