Effects of Rosin-Aluminum Sulfate Treatment on the Leachability, Color Stability, and Decay Resistance of Wood Treated with a Boron-Based Preservative

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This study evaluated the combined effects of rosin and aluminum sulfate (alum) on the leachability of boron, the color stability, and the decay resistance of poplar (*Populus ussuriensis*) wood treated with boron compounds. After leaching, the boron content in the leachates was analyzed *via* the azomethine-H method. Results showed the amount of boron released from the rosin-alum-boron solution treated samples was reduced by approximately 30% when compared to the samples treated with boric acid alone. All samples treated with rosin-alum-boron formulations exhibited greater color stability than that of the untreated controls after being exposed to natural weathering. The decay resistance of the treated wood blocks was measured *via* a soil-block culture. The results revealed that after being treated with the rosin-alum-boron formulations, the decay resistance of the leached wood was markedly improved. The average weight loss of the samples degraded by both fungi tested was less than 20%. Notably, scanning electron microscopy equipped with an energy dispersive X-ray analysis showed that the B element was still in the cell lumens of the leached and decayed wood blocks. This signified that the use of rosin combined with aluminum sulfate as a fixative agent may reduce boron leachability and could increase the usage of wood treated with boron preservatives.

Keywords: Rosin-Aluminum; Color stability; Leaching resistance; Decay resistance; Boric acid; Weathering

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INTRODUCTION

Wood, in its many forms, has been one of the most versatile materials for buildings, constructs, or furniture due to its superior material properties; *e.g.* its pleasing optical appearance, favorable mass to strength ratio, and low thermal conductance. However, wood also has some negative aspects, most notably its dimensional instability when subjected to changing moisture content, expressed photo-yellowing, and its susceptibility to deterioration *via* microorganisms and insects. These problems can be partially overcome *via* the modification or impregnation of the wood.

Boron compounds have also been used as a low-toxicity preservative. The efficacy of boric acid and borates against wood decay fungi, termites, and fire has been noted and utilized in wood products for many years (Ngoc 2006). Despite the many advantages of boron compounds, boron itself does not adequately protect wood with contact to the ground or with an exterior application, because of its natural diffusibility and susceptibility to leaching (Yalinkilic 2000). To increase the use of boron compounds as an environmentally

benign wood preservative, several fixation systems to limit or decrease the leachability of boron from treated wood have been developed. For example, water repellents or polymer systems were used to reduce the leaching in treated timber (Murphy *et al.* 1995). In addition, Yamaguchi (2003; 2005) showed that a combination of silicic acid and boric acid contributed to a higher water resistance ability in treated wood, which increased the fungal and termite resistance of leached wood specimens. More recently, a combination of boron compounds with commercial silicon emulsion was also applied to decrease boron leaching from treated wood (Kartal *et al.* 2007); or combined with tall oil derivates to fix boron in wood cells for protection against fungi and termites (Temiz *et al.* 2008); and combination with plant oils to decrease boron leaching and improve thermal degradation of wood (Tomak *et al.* 2011). Some researchers used natural resources as raw materials or combined with boron compounds to investigate the development of new effective, economically practicable, and environmentally friendly preservation systems (Obanda *et al.* 2008; Sen *et al.* 2009; Köse *et al.* 2011; Lesar *et al.* 2012; Tondi *et al.* 2012). However, due to the high costs, or the need for a two-step treatment process, the above-mentioned approach could not have been applied in practice.

Rosin is a natural product, obtained from pines and some other plants. The major component of rosin is abietic acid, a partially unsaturated compound with three fused six-membered rings and one carboxyl group, and therefore it has strong hydrophobic properties (Song 2002). Over the years, rosin has been widely used in the paper industry as a sizing agent (Zhang 2005). In recent decades, rosin has been combined with copper to treat wood, *e.g.*, rosin-copper soaps obtained when dissolved in a solvent (ethanol), which has been found to be extremely efficient in reducing both fungi and termite deterioration (Pizzi 1993a,b). Roussel *et al.* (2000) also used a non-solvent rosin-copper formulation to impregnate the wood, but a double impregnation system was required. Subsequently, the authors used a rosin-sizing agent and a water-borne rosin-copper compound to impregnate poplar wood. The results showed that the rosin could decrease the moisture absorption ability of wood and help improve the decay resistance of the wood (Li *et al.* 2011; Nguyen and Li 2014). In particular, the rosin had a very high copper fixing efficiency in wood, and wood samples treated with the rosin-copper compound had a greater decay resistance, even after leaching (Nguyen *et al.* 2012; Nguyen *et al.* 2013a). In addition, the author's earlier investigation showed that a rosin sizing agent also had a certain effect on the fixation of boron in wood samples (Nguyen and Li 2017). Therefore, this paper deal with a new rosin-aluminum-boron formulation for fixation of boron into treated wood and developing an effective wood preservative with low toxicity, that was environmentally friendly, and had good overall performance, but was also low cost. Moreover, the influence of the combined rosin-alum and the boron treatment on the decay resistance and color stability of the treated wood was also discussed.

EXPERIMENTAL

Preparation of Test Specimens and Chemicals

Wood samples with two different configurations were prepared from untreated poplar sapwood (*Populus ussuriensis* Komo). The specimen dimensions were 20 mm × 20 mm × 20 mm for the leaching and decay tests and 145 mm × 50 mm × 5 mm for the weathering (length, width, and thickness, respectively). In addition, feeder strips (22 mm

× 22 mm × 3 mm) were also prepared from poplar sapwood. One feeder strip was needed for each cube in a culture bottle for the decay test.

The anionic rosin emulsion sizing agent (R) was an industrial product and was supplied by Guangxi Wuzhou Arakawa Chemical Industries Co., Ltd (Nanning, China). In this study, it was used to impregnate the wood at three concentrations (1%, 2%, and 4%). Boric acid (H_3BO_3), with a concentration of 3%, was used as a preservative to protect the wood against fungal decay. In addition, aluminum sulfate ($Al_2(SO_4)_3$) was used and combined with the rosin emulsion sizing agent, as well as boric acid, to impregnate the wood samples (with a concentration of 1%). All of the chemical reagents used in this work were analytical grade and were supplied by Tianjin Kermel Chemical Reagent Co., Ltd (Tianjin Shi, China).

Impregnation Method

Before treatment, all samples were oven-dried at 103 °C overnight and weighed to the nearest 0.01 g and recorded as W_1. The samples were then treated with the treatment solutions using a full-cell pressure process at a 0.1 MPa vacuum for 30 min. Followed this, the samples were remained in the solutions by air pressure for 1 h. The blocks were then individually removed from the solution, wiped lightly to remove the rest of the solution from the wood surface, and immediately weighed (W_2). The retention of each block was calculated using the Eq. 1,

$$\text{Retention}\left(\frac{\text{kg}}{\text{m}^3}\right) = \frac{G \times C}{V} \times 10 \quad (1)$$

where G, which equaled W_2 - W_1, is the weight (g) of the treatment solution absorbed by the block, C is the weight (g) of the preservative in 100 g of the treatment solution, and V (cm^3) is the volume of the block.

After calculating the total retention, the samples were conditioned at 65% RH and 22 °C for 2 weeks prior to undergoing the other tests.

Leaching Process

The leaching process was conducted according to the AWPA E11-06 (2007) standard. After air-drying, twelve treated blocks per treatment were immersed in beakers of distilled water, over which a vacuum was applied for 30 min. Then the vacuum was released, the wood blocks were still immersed in the distilled water. After 6 h, 24 h, and 48 h, and thereafter at 48 h intervals, the leaching water was removed and replaced with an equal amount of fresh distilled water. The leaching process was carried out for a total of 14 d. All leachates were collected and kept for boron analysis.

Analysis of Leachates for Boron

In order to measure the boron content leached from the treated wood blocks, the leachates were analyzed *via* the azomethine-H method described by John *et al.* (1975) and following the method described by the AWPA A2-07 (2007) standard.

Microscopic Observation

Small samples with a dimension of 10 mm × 10 mm × 1 mm were cut from the untreated control and the treated wood blocks using a razor blade. Each sample was mounted on a metal stub with adhesive, and then they were placed under a vacuum and were sputter-coated with a thin layer (approximately 20 nm thick) of gold. The samples

were then observed with a scanning electron microscope (SEM) (FEI Company, Quanta 200, Hillsboro, OR, USA) at an accelerating voltage of 20 kV. Random observations were made on different structures to identify the existence of boron in the anatomical structure of the samples. The element composition was determined *via* regional analysis using an energy dispersive X-ray spectrometer (EDX) (FEI Company, Quanta 200, Hillsboro, OR, USA) combined with the SEM.

Weathering Exposure

The specimens were exposed to natural weathering conditions from the 15th of April to the 15th of July (2019). The weathering site was located at the Vietnam National University of Forestry in Ha Noi, Vietnam. The weather conditions for Ha Noi during the weathering period are shown in Table 1.

Table 1. Climate Conditions of Ha Noi City during the Weathering Period

Month	March	April	May	June	July
Average Temperature (°C)	22.6	27.5	28.3	31.6	31.6
Highest Temperature (°C)	25.9	31.4	31.8	36.2	36.2
Lowest Temperature(°C)	20.6	25.2	25.9	28.7	28.7
Total rainfall per month (mm)	15	166	97	97	97
Number of rainy days	12	15	19	11	11

Source: (IMHEN 2019)

The exposure rack was positioned so that the exposed specimens were at a 45° angle facing south. The wood specimens were set outside for weathering exposure according to ASTM G7/G7M-13 (2013). The exposure period was 3 months. Color measurements were made on the exposed surfaces of the wood specimens before and after weathering and the assessment of the weathered samples consisted of color measurement.

Color Measurement

The color of the wood surfaces was calculated before and after weathering and was performed *via* an NF–333 Spectrophotometer (Nippon Denshoku Industries Co. Ltd., Tokyo, Japan). The CIELAB system is characterized by three parameters, L^*, a^*, and b^*. The L^*, a^*, and b^* color coordinates for each sample were determined before and after exposure to weathering. These values were used to calculate the color change, ΔE^*, as a function of the UV irradiation period according to Eqs. 2 through 5,

$$\Delta L^* = L^*_f - L^*_i \quad (2)$$

$$\Delta a^* = a^*_f - a^*_i \quad (3)$$

$$\Delta b^* = b^*_f - b^*_i \quad (4)$$

$$\Delta E^* = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \quad (5)$$

where ΔL^*, Δa^*, and Δb^* are the changes between the initial (i) and final (f) values. The changes in L^*, a^*, and b^* values contribute to the overall color change, ΔE^*. A low ΔE^* corresponded to a low color change, *i.e.* a stable color.

Decay Test

The decay resistance test for the treated wood blocks was conducted according to Chinese standard LY/T 1283-1998 (1998) after exposure to the white-rot fungus (*Trametes versicolor*) and the brown-rot fungus (*Gloeophyllum trabeum*). First, the soil culture bottles with the feeder strips on the soil surface were sterilized for 60 min, and then inoculated with a fungus, which was cultured on potato dextrose agar. After the feeder strips were covered with fungal mycelium, the sterilized wood blocks were placed onto the feeder strip. The soil-block culture was incubated in a temperature and humidity controlled chamber at 28 ± 2 °C and 75% relative humidity for 12 weeks. Then the blocks were removed from the decay bottles, brushed free of mycelium, dried at 103 °C until a constant weight was obtained, and then weighed to determine weight loss.

RESULTS AND DISCUSSION

Retention Results

The total retention amounts of different impregnation solutions on poplar wood are shown in Table 2. It was clearly shown that a higher rosin concentration led to a higher total retention weight.

Table 2. Retention Levels of Wood Samples Treated with Solutions

Abbreviation	Solutions and Concentrations	Retention (kg/m^3)[a]
1	1% R	7.9 (0.32)
2	2% R	15.83 (0.94)
3	4% R	31.72 (0.39)
4	3% BA	23.45 (0.90)
5	1% R + 3% BA	31.62 (0.99)
6	2% R + 3% BA	38.12 (1.34)
7	4% R + 3% BA	52.52 (2.77)
8	1% R+3% BA+1% Al	40.50 (2.36)
9	2% R+3% BA+1% Al	47.54 (8.75)
10	4% R+3% BA+1% Al	68.42 (2.63)

Note: R = rosin sizing agent; BA = boric acid (H_3BO_3); Al = aluminum sulfate ($Al_2(SO_4)_3$); [a]: All results are means of 24 samples. Standard deviations are in brackets.

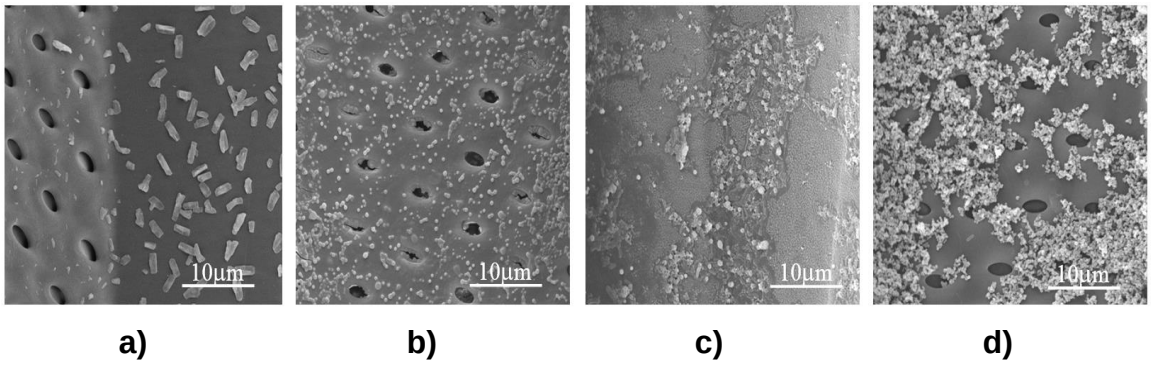

Fig. 1. SEM images with a magnification of 10 μm showing tangential sections of the poplar samples treated with boron alone, or in combination with rosin and aluminum: (a: 3% BA; b: 4% R; c: 2% R + 3% BA; d: 2% R + 3% BA + 1% Al)

The total uptake of the treatment solutions by the poplar wood samples, including both rosin alone, and in combination with aluminum sulfate (alum) and/or boric acid in the same concentration, were relatively equal. Additionally, the SEM micrographs (Fig. 1) showed that various preservative complexes were found in the cell lumens of the vessels, and several vessels were even clogged by these complexes. These results suggested that all the treatment solutions used in this study successfully penetrated the wood blocks during the impregnation step. This result agreed with the results demonstrated in previous reports (Nguyen *et al*. 2012, 2013b; Nguyen and Li 2017).

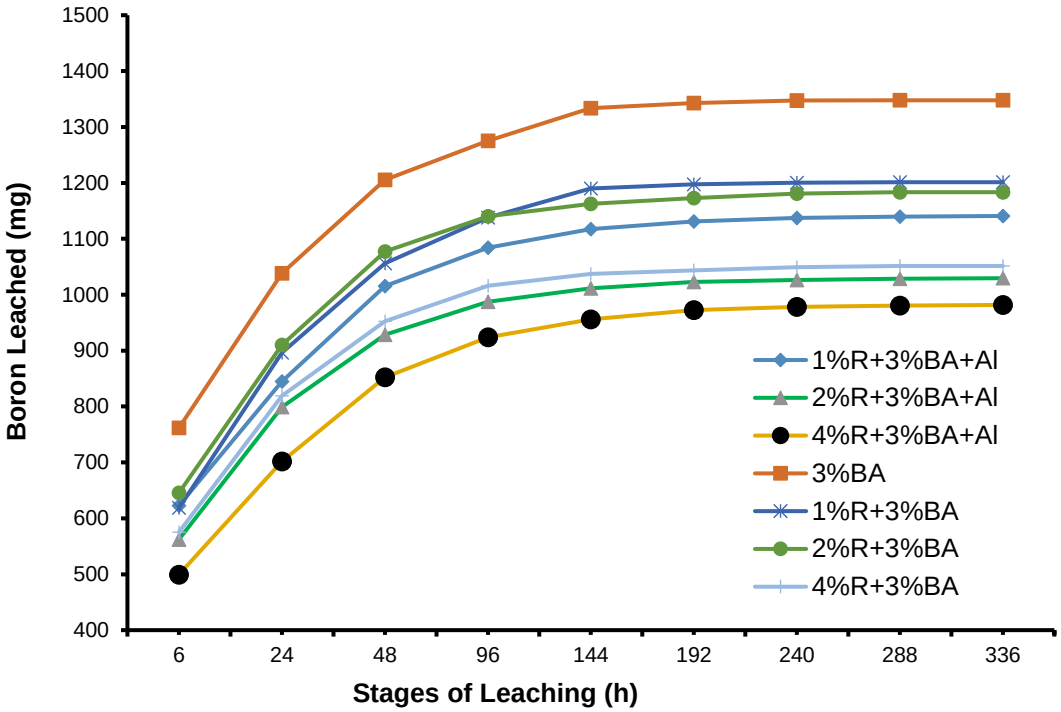

Fig. 2. The boron contents released from the treated wood specimens at different time intervals (BA = boric acid (H_3BO_3); R = rosin sizing agent; Al = aluminum sulfate)

Boron Leachability

Figure 2 presents the amount of boron released from the wood samples treated with just boric acid solution, or in combination with rosin-alum at different time intervals. Results showed that nearly all the boron was leached out from the boric acid-only treated wood samples. After 14 days of leaching, 1350 mg of boron had been leached out from the samples, which represented 93% of the boron impregnated in the wood blocks.

However, after rosin at a concentration of 1%, 2%, or 4% was added, the observed leaching of the boron was 1203 mg, 1187 mg, and 1055 mg, respectively. In comparison to the treated samples with boric acid alone, the extent of boron leaching was reduced by 11%, 12%, and 22%, respectively. These results suggested that the rosin can contribute to the improvement of boron fixation in wood. In addition, the total amount of leached boron ions slightly decreased with an increase in rosin concentration in the impregnation solution. This was probably due to the hydrophobic property of rosin.

After having penetrated the wood blocks, the rosin molecules were present in the cell lumen, and formed an adhesive film that covered the boron crystals (Nguyen *et al.* 2013a). During the leaching process, the rosin acted as a barrier, which prevented the water from entering the wood and slowed down the release of boron from deep inside the samples. Moreover, after aluminum sulfate was applied to the wood together with rosin and boric acid, the observed leaching of boron was reduced by approximately 30%. This reduction could be explained by both the rosin and the boric acid having a negative charge, as well as the surface of the fiber having a negative charge. Therefore, the rosin and boron could not directly bond to the fiber. Aluminum sulfate is an electrolyte, which can be hydrolyzed and ionized to form a large number of positively charged ions during the impregnation process and combined with the negatively charged rosin and boron ions. When the positive and negative charges in the system reach an isoelectric state, the rosin formed a stronger bond with the elemental boron and the wood cell walls (Wu 1995; Wu *et al.* 2010). Besides, the rosin could bond to the wood-fibers through hydrophobic effect and hydrogen-bonding affinity. When wood samples were impregnated with a solution with an increased rosin concentration, a greater amount of rosin ended up on the surface of the treated wood, thereby reducing the amount of boron ions diffusing from the wood during the leaching process.

Color Stability

The change in color was the most important factor in the weathering evaluation. Figure 3 and Table 3 present the L^*, a^*, and b^* values for the untreated (control) and the impregnated specimens before being exposed to natural weathering. In addition, the change in value for all three color parameters (ΔL^*, Δa^*, and Δb^*) were illustrated, as well as the total change in color (ΔE^*) of the wood specimens after 3 months of natural weathering. Before weathering, the L^*, a^*, and b^* values of the untreated (control) poplar wood specimens were 82.6, 6.2, and 16.4, respectively. The L^* values of the impregnated poplar wood specimens changed from 79.9 to 84.8, the a^* values changed from 3.8 to 6.4, and the b^* values changed from 15.1 to 20.3. These results showed that poplar wood had a light, yellowish, and reddish color before exposure to natural weathering and all treatments in this study had no effect on the natural color of the poplar wood (Fig. 3). However, after exposure to 3 months of natural weathering, the Δa^* values were decreased to a value range of -0.1 to -3.0. The negative Δa^* values showed that the wood surface turned from red to green. The Δb^* values decreased to a range of -5.4 to -10.4. The negative Δb^* values indicated that the untreated and treated poplar wood surfaces had a tendency to becoming

bluer after weathering. The Δ*L** values, which Baysal (2012) noted was the most sensitive parameter of the wood surface quality, which decreased to a range of -15.4 to -25.5. The negative lightness stability (Δ*L**) values for both the untreated and treated poplar samples showed that the wood surface became darker after natural weathering. The darkening of the poplar wood might have been due to the degradation of the lignins and other non-cellulosic polysaccharides (Hon 1981; Grelier *et al.* 2000). However, all preservative-treated poplar samples experienced less change in the lightness than the untreated samples in this study. This may have been due to the fact that the preservative impregnation improved the resistance against fungal attack (Fig. 3). In addition, the stabilization of the wood color in the visible region may have occurred from a reduction in lignin degradation, which was due to UV light irradiation (Hon 1981). The total color change (Δ*E**) of the untreated poplar was 26.3, while it ranged from 18.2 to 23.6 for the treated poplar specimens after weathering. Moreover, one-way ANOVA analysis revealed that the Δ*E** values of the treated poplar wood specimens were significantly less than that of the untreated poplar wood specimens. This suggested that poplar wood treated with the mixture of rosin, boric acid, and aluminum sulfate exhibited greater color stability than that of the untreated poplar wood after weathering. The greatest color stability was obtained with the rosin-boron treated samples after weathering. However, the rosin concentration had no significant impact on the color stability of the wood samples treated with rosin alone, or in combination with boric acid and aluminum sulfate.

Fig. 3. Photographs of poplar wood samples before and after 3 months of natural weathering

Table 3. Color Change of Poplar Wood before and after Natural Weathering

Solutions and Concentrations	Retention (kg/m³)	Before Natural Weathering		
		L	*a*	*b*
1% R	7.9 (0.32)	80.26^{a} (2.64)	6.00^{cd} (0.68)	18.51^{c} (1.23)
2% R	15.83 (0.94)	81.68^{a} (1.29)	5.47^{bc} (0.54)	19.47^{cd} (1.46)
4% R	31.72 (0.39)	80.20^{a} (2.46)	6.38^{cd} (0.65)	19.01^{cd} (1.84)
3% BA	23.45 (0.90)	81.59^{a} (2.21)	6.29^{cd} (1.00)	18.26^{c} (1.26)
1% R + 3% BA	31.62 (0.99)	80.44^{a} (3.99)	6.15^{cd} (1.16)	19.06^{cd} (1.38)
2% R + 3% BA	38.12 (1.34)	81.43^{a} (1.77)	5.90^{cd} (0.94)	18.54^{c} (1.03)
4% R + 3% BA	52.52 (2.77)	79.87^{a} (1.72)	6.38^{cd} (0.82)	20.30^{d} (0.88)
1% R + 3% BA + 1% Al	40.50 (2.36)	84.35^{b} (1.47)	4.83^{a} (0.47)	15.78^{ab} (1.42)
2% R + 3% BA + 1% Al	47.54 (8.75)	84.32^{b} (2.76)	4.58^{ab} (0.48)	15.61^{ab} (0.88)
4% R + 3% BA + 1% Al	68.42 (2.63)	84.77^{b} (1.65)	3.84^{a} (0.50)	15.08^{a} (0.85)
Control	-	82.56^{ab} (3.12)	6.19^{cd} (0.92)	16.42^{ab} (0.53)
Solutions and Concentrations	After Natural Weathering			
	Δ*L*	Δ*a*	Δ*b*	Δ*E*
1% R	-21.17^{bcd} (3.28)	-2.10^{ab} (0.73)	-8.55^{a} (1.16)	22.97^{cd} (3.21)
2% R	-21.65^{bc} (0.70)	-1.10^{c} (0.56)	-8.90^{a} (1.36)	23.46^{d} (1.02)
4% R	-19.68^{cd} (2.54)	-1.68^{abc} (0.54)	-7.68^{ab} (1.76)	21.30^{bcd}(2.19)
3% BA	-18.66^{d} (1.96)	-2.51^{a} (1.06)	-8.19^{a} (0.92)	20.61^{abc}(1.53)
1% R + 3% BA	-15.67^{e} (3.41)	-2.14^{ab} (1.29)	-8.71^{a} (1.23)	18.21^{a} (2.89)
2% R + 3% BA	-16.54^{e} (2.86)	-1.90^{abc} (0.84)	-8.35^{a} (0.96)	18.70^{ab} (2.57)
4% R + 3% BA	-15.36^{e} (1.78)	-3.03^{a} (0.83)	-10.45^{a}(0.93)	19.01^{ab} (1.43)
1% R + 3% BA + 1% Al	-21.45^{bc} (3.97)	-1.33^{bc} (0.59)	-6.36^{cd} (1.32)	22.49^{cd} (3.77)
2% R + 3% BA + 1% Al	-22.38^{bc} (2.93)	-1.30^{bc} (0.67)	-6.70^{bc} (0.69)	23.42^{d} (2.84)
4% R + 3% BA + 1% Al	-22.88^{ab} (1.54)	-0.06^{d} (0.54)	-5.41^{d} (1.18)	23.55^{d} (1.50)
Control	-25.49^{a} (2.49)	-1.93^{abc} (1.08)	-6.00^{cd} (0.71)	26.29^{e} (2.33)

Note: R = rosin sizing agent; BA = boric acid (H_3BO_3); Al = aluminum sulfate ($Al_2(SO_4)_3$). Values in parenthesis are standard deviations and the different letters indicate a significant difference by Duncan's homogeneity test (P value less than 0.05).

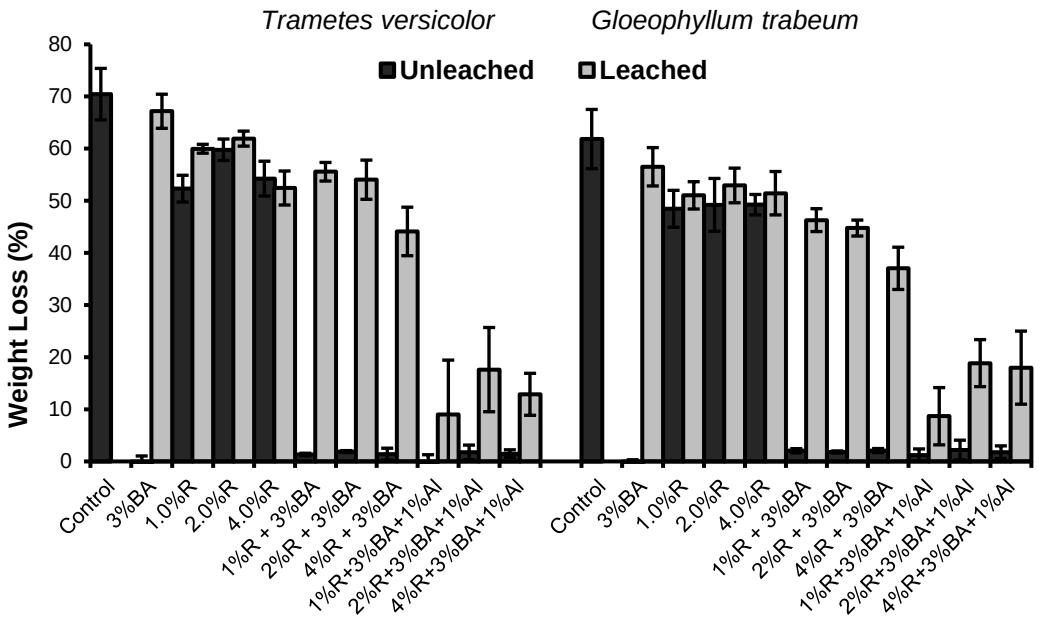

Fig. 4. The combined effects of rosin-aluminum on the decay resistance of wood blocks treated with boron-based preservatives against *Trametes versicolor* and *Gloeophyllum trabeum*

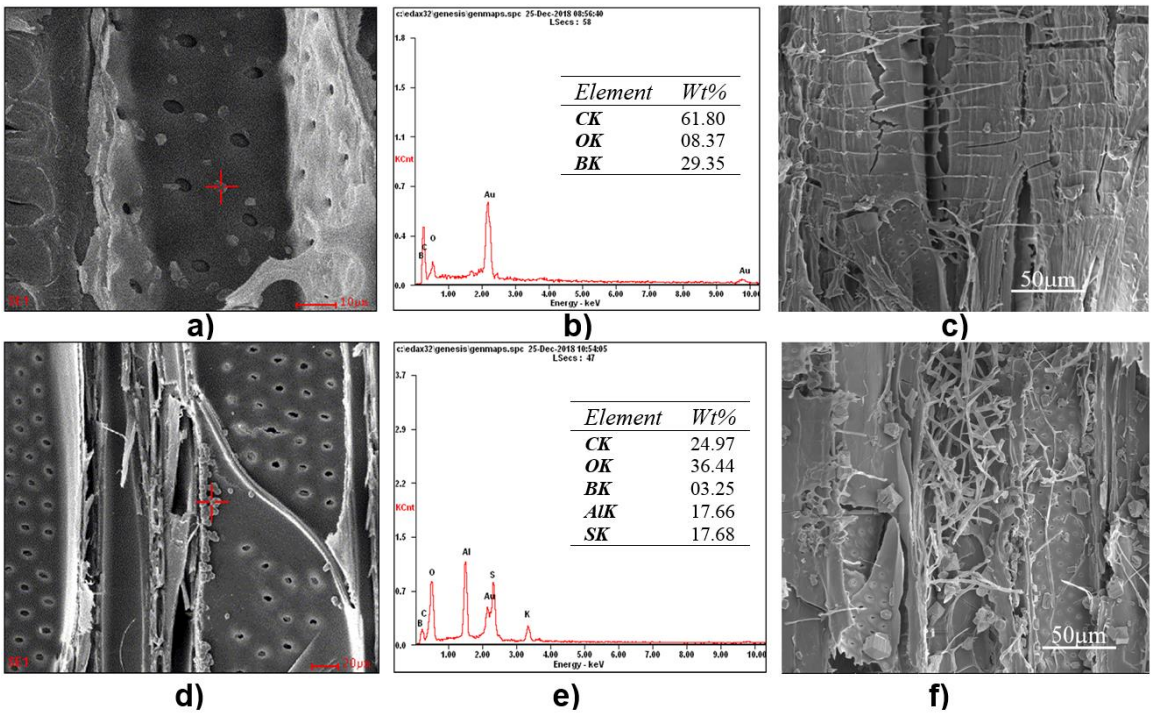

Fig. 5. SEM images and corresponding spectra of the tangential section of the treated wood blocks after being exposed to fungus: (a and b) unleached samples and (c) leached samples with a magnification of 10 µm of wood blocks treated with boron alone; (d and e) leached wood-block treated with rosin-aluminum-boron; and (f) untreated control

Decay Resistance

The decay resistance of the leached wood blocks treated with boric acid alone, or in combination with rosin-aluminum preservatives, against *T. versicolor* and *G. trabeum* are reported in Fig. 4. Each decay resistance value was the mean representing six wood blocks. As shown in Fig. 4, and results reported in previous research by Nguyen *et al.* (2012), the weight loss of the control wood blocks due to *T. versicolor* was 70.4% and was 61.8% for *G. trabeum*. For the samples treated with only rosin sizing agents, the total weight loss ranged from 48% to 55%. In addition, no remarkable changes in the total weight loss values were observed between the samples treated with all concentrations of rosin (1.0%, 2.0%, or 4.0%) as well as the leached and unleached samples. However, when the samples were treated with boric acid alone, a severe total weight loss (67.2% for *T. versicolor* and 56.5% for *G. trabeum*) were found for the leached wood samples, while the unleached wood blocks exhibited an approximate weight loss of 2% for both test-fungi. In addition, microscopic observations of the unleached wood-block treated with boric acid after being exposed to fungus showed that various crystal particles were found in the lumens, as well as cell walls (Fig. 5a) and the spot analysis using SEM-EDX proved that these particles contained greater amounts of element B (Fig. 5b). However, when the leached wood-block was examined (Fig. 5c), the wood cell walls had been completely destroyed by the fungi, similar to that of the untreated controls (Fig. 5f), which showed that nearly all the boron had been leached out from the wood. This result was in accordance with that reported by Tomak *et al.* (2011).

However, when rosin was combined with boric acid to impregnate wood, the average weight loss of the leached wood blocks degraded by fungi ranged from 37.0% to

55.6%. Compared to the untreated samples or the samples treated with boric acid alone, this was a significant decrease. These results showed that the rosin sizing agent had a positive effect on the fixation of boron in wood. Hence the boron-rosin formulations showed better resistance against fungal decay compared to the boric acid alone. Notably, after aluminum sulfate was injected into the wood with the rosin and boric acid, the wood decay resistance was notably improved. The average weight loss from the decay test of the rosin-aluminum-boron treated samples after leaching ranged from 8.7% to 18.9%, which was significantly lower than that of the untreated samples or the samples treated with boric acid only. Furthermore, the microscopic observations of leached wood samples treated with rosin-aluminum-boron after being subjected to fungal decaying, showed various spherical agglomerates in the cell lumen (Fig. 5d). The spectrum obtained from the spot analysis confirmed that these agglomerates contained element B (Fig. 5e). This signified that boron had been retained in the wood blocks after leaching, thus, the rosin-aluminum-boron formulations showed greater resistance against fungal decay than the acid boric or rosin-boron formulations did. The greatest decay resistance was found in the samples treated with 1% rosin, 3% boric acid, and 1% aluminum sulfate.

CONCLUSIONS

1. Combinations of rosin sizing agents and aluminum sulfate with boric acid had a synergetic effect on the fixation of boron in wood. The boron ion content released from the samples treated with the rosin-aluminum-boron solutions was reduced by approximately 30% when compared with those from the samples treated with boric acid alone. Furthermore, the wood blocks treated with rosin-aluminum-boron formulations were more effective against both *Trametes versicolor* and *Gloeophyllum trabeum* than those treated with rosin-boron solutions or boric acid alone after leaching.
2. The results of the weathering tests showed that poplar wood treated with a mixture of rosin, boric acid, and aluminum sulfate exhibited greater color stability than that of the untreated poplar wood. The least changes in the color values were observed for the rosin-boron treated samples.
3. The SEM observation and EDX analysis of the wood blocks treated with rosin-aluminum-boron formulations confirmed that the preservative complexes containing B were present in the cell lumens of the leached and decayed wood blocks. These results signified that the use of rosin combined with aluminum sulfate as a fixative agent may reduce boron leachability and could increase the usage of wood treated with boron preservatives.

ACKNOWLEDGEMENTS

The authors are grateful for the support of the Vietnam National Foundation for Science and Technology Development (NAFOSTED) under grant number 106.99-2018.16.

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Article submitted: September 8, 2019; Peer review completed: October 19, 2019; Revised version received and accepted: November 7, 2019; Published: November 12, 2019.
DOI: 10.15376/biores.15.1.172-186