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ORIGINAL ARTICLE

Comparison of physical and mechanical properties of *Paulownia tomentosa* and *Pinus koraiensis* wood heat-treated in oil and air

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Abstract

This study aimed to determine and compare the effects of heat treatment in palm oil and air on the physical and mechanical properties of *Paulownia tomentosa* and *Pinus koraiensis* wood. The heat treatment was conducted at 180, 200, and 220 °C for 1, 2, and 3 h. The characteristics of the wood before and after heat treatment, such as density, volume shrinkage, abrasion, axial compressive strength, and hardness, were investigated. Heat treatment in oil caused a significant increase in wood density, whereas the density of air heat-treated wood decreased. Oil heat-treated wood exhibited lower volume shrinkage and weight loss in abrasion compared to air-heat-treated wood. The axial compressive strength of both wood samples heat-treated in oil and air was the highest at 180 °C, and then gradually decreased as the temperature and treatment duration increased. Oil heat treatment increased the hardness of *Pinus koraiensis* wood, in contrast to *Paulownia tomentosa* wood. The hardness of both wood samples decreased with air heat treatment. In conclusion, it was revealed that there were some differences in the effect of physical and mechanical properties by heat treatment methods between wood species. Oil heat treatment was a more effective method for improving the properties of both woods compared to air heat treatment.

1 Introduction

As mentioned in a previous research (Suri et al. 2021), Korea imports more than 80% of its wood demand from overseas countries, including Indonesia, New Zealand, North America, and other countries. To reduce dependence on imported wood, it is necessary to explore and evaluate the domestic timber resources. Domestic fast-growing wood species, such as *Paulownia tomentosa* and *Pinus koraiensis,* are important species to be developed to raise the timber resources in Korea.

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Paulownia wood is a hardwood that can be found worldwide (Caparrós et al. 2008). *Paulownia* wood has excellent timber characteristics, such as fast growth, clear wood grain, high dimensional stability, low shrinkage, and relative durability against rot and termites (Akhtari et al. 2011; Icka et al. 2016; Esteves et al. 2021). *Paulownia* wood has generally been used as a material for construction, furniture, pulp, handicrafts, particleboard, paper production, bioenergy application, and musical instruments (Chong and Park 2008; Akyildiz and Kol, 2010; Lopez et al. 2012; Qi et al. 2016; Kang et al. 2019).

Pinus koraiensis is an indigenous and widely planted tree species for commercial utilization in Korea (Son et al. 2007). The wood has high growth rate and low shrinkage (Chong and Park, 2008) and is suitable for furniture, particleboard and fiberboard manufacturing, as well as building materials for wood ships (Son et al. 2001; Chong and Park, 2008; Li et al. 2020).

However, *Paulownia tomentosa* wood has a low density and mechanical properties (Chong and Park, 2008; Akyildiz et al. 2011). *Pinus koraiensis* wood also has lower density and natural durability concerning wood fungi compared to other pine woods (Chong and Park, 2008). The woods from both species also have a light cream or light pale brown color, which is not of aesthetical advantage for some applications.

Heat treatments in different kinds of atmospheric conditions, including air, nitrogen, steam, oil and vacuum, have been reported for improving some wood properties (Tjeerdsma and Militz 2006; Welzbacher et al. 2008; Hakkou et al. 2005; Boonstra et al. 2007a; Dubey et al. 2012; Surini et al. 2012).

Air heat treatment is the most popular and well-established method for wood modification (Hill, 2006; Militz and Altgen, 2014). Air heat treatment of wood can be applied to improve dimensional stability, hygrophobicity, durability, color, and reduce equilibrium moisture content (Esteves and Pereira, 2009; Hidayat et al. 2015). Although there is an improvement in some physical properties of wood after heat treatment at temperatures ranging from 180–260 °C, it is usually accompanied by a decrease in mechanical strength (Hill, 2006). Herrera-Díaz et al. (2019) reported a significant improvement in dimensional stability and a decrease in MOR in *Pinus radiata* wood by heat treatment. Nevertheless, infrequently, the mechanical properties of wood after heat treatment showed positive results, namely, increasing the value of several properties. Boonstra et al. (2007b) reported that the compressive strength of *Pinus sylvestris* wood increased after heat treatment in air at 165 °C and 185 °C for 90 min by 28%. In addition, Boruvka et al. (2018) reported that the hardness of radial and tangential surfaces of air-heat-treated *Betula pendula* wood increased after heat-treatment at 165 °C and 210 °C.

Recently, oil heat treatment has become a common method to improve wood properties owing to the combined effects of oil and heat. The oil can separate oxygen from the wood during heat treatment and prevent oxidative processes, which causes a slight decrease in the strength of the treated sample (Dubey et al. 2011). Its ability to transfer heat to wood more efficiently and evenly is one of the main factors in using oil as a heating medium (Umar et al. 2016). Some related studies have demonstrated the excellent results of wood modification by oil heat treatment. Lee et al. (2018) explained that oil-heat-treated wood showed superior dimensional stability compared to wood treated in hot air and nitrogen. Oil heat treatment can also be applied to improve wood for outdoor use and to discolor the surface uniformly (Sailer et al. 2000). Oil uptake during oil heat treatment contributes to improving fungal resistance and uniformly darkening the wood surface color (Dubey et al. 2012). Okon et al. (2018) reported increased density and reduced shrinkage in *Cunninghamia lanceolata* wood by oil heat treatment. Cheng et al. (2014) reported that the compression strength parallel to the grain of *Populus spp.* wood increased by oil heat treatment, which might be due to cell wall thickening and lumen filling by oil.

As mentioned above, there are many studies on the effect of heat treatment under different conditions on the wood properties. In a previous research, the color change of *Paulownia tomentosa* and *Pinus koraiensis* wood between hot oil and hot air treatments was compared (Suri et al. 2021). However, there is still a lack of information on a comparative study of the effect of heat treatment in oil and air on the physical and mechanical properties. In particular, there is no trial study of the improvement of the wood quality of *Paulownia tomentosa* and *Pinus koraiensis* wood using oil heat treatment. Therefore, this study aimed to determine and compare the effects of heat treatment in palm oil and air on the physical and mechanical properties of *Paulownia tomentosa* and *Pinus koraiensis* wood to further utilize the fast-growing wood species in Korea.

2 Materials and methods

2.1 Materials

Three trees each of *Paulownia tomentosa* and *Pinus koraiensis* were obtained from the research forest of Kangwon National University, Chuncheon, Korea. The basic information of the experimental trees is presented in Table 1. The logs were converted into quarter-sawn boards and the boards with straight-grain and free from defects were selected for the experiment. The board samples were oven-dried and conditioned in a desiccator at 25 ± 5 °C and relative humidity of 50%–65% for a few days until reaching equilibrium moisture content for further testing.

Table 1 Basic information on the sample trees

Common name	Scientific name	Age (years)	D.B.H (cm)	Air-dried density (g/cm^3)	Location
Royal paulownia	*Paulownia tomentosa* (Thunb.) Steud	15 to 20	28 to 33	0.30 (0.05)	Chuncheon, Korea (N 37°77`, E 127°81`)
Korean white pine	*Pinus koraiensis* Siebold & Zucc	30 to 35	28 to 32	0.42 (0.05)	

*Numbers in parentheses are standard deviations

2.2 Heat treatment

Oil heat treatment was performed in a lab-scale oil bath with 5 l volume (C-WHT-S2; ChangShin Science, Seoul, Korea) using commercial palm oil (Lotte foods, Seoul, Korea). The samples were soaked in oil at room temperature, heated to target temperatures of 180, 200, and 220 °C with a heating rate of 2 °C/min, and treated for 1, 2, and 3 h, respectively. After the oil heat treatment, the wood samples were left in oil for a few hours until cooling, and then the samples were drained at 27.5 ± 3 °C and RH 60 ± 5% for 24 h.

Air heat treatment was performed in an electric furnace (Supertherm HT16/16; Nabertherm GmbH, Lilienthal, Germany). The temperature was raised from room temperature to the target temperatures of 180, 200, and 220 °C for 1, 2, and 3 h at a heating rate of 2 °C/min. In the final stage of the heat treatment, the furnace chamber was allowed to cool naturally to room temperature.

All wood samples heat-treated in oil and air were oven-dried at 105 ± 3 °C for 24 h and then kept in a desiccator with silica gel for a week until further testing.

2.3 Evaluation of the heat-treated wood samples

Detailed information regarding the physical and mechanical properties of the specimens is presented in Table 2. The formulas used to calculate the physical and mechanical properties are listed in Table 3.

The density and volume shrinkage of untreated and treated woods were determined using ten specimens each

Table 2 Sample information for evaluating the physical and mechanical properties of the heat-treated woods

Test	Sample dimension	Species	Treatment	Temperature and duration	Sample number	Total
Density	40 (L) × 20 (R) × 20 (T) mm^3 (KS F 2198 (2016))	*Paulownia tomentosa* and *Pinus koraiensis*	Oil and air heat treatment	Control	10 × 2	380
				180 °C for 1, 2, 3 h	10 × 2 × 2 × 3	
				200 °C for 1, 2, 3 h	10 × 2 × 2 × 3	
				220 °C for 1, 2, 3 h	10 × 2 × 2 × 3	
Volume shrinkage	40 (L) × 20 (R) × 20 (T) mm^3 (KS F 2203 (2004))	*Paulownia tomentosa* and *Pinus koraiensis*	Oil and air heat treatment	180 °C for 1, 2, 3 h	10 × 2 × 2 × 3	360
				200 °C for 1, 2, 3 h	10 × 2 × 2 × 3	
				220 °C for 1, 2, 3 h	10 × 2 × 2 × 3	
Abrasion	100 (L) × 100 (R) × 10 (T) mm^3 (KS F 2215 (2006))	*Paulownia tomentosa* and *Pinus koraiensis*	Oil and air heat treatment	Control	3 × 2	42
				180 °C for 2 h	3 × 2 × 2	
				200 °C for 2 h	3 × 2 × 2	
				220 °C for 2 h	3 × 2 × 2	
Axial compressive strength	40 (L) × 20 (R) × 20 (T) mm^3 (KS F 2206 (2004))	*Paulownia tomentosa* and *Pinus koraiensis*	Oil and air heat treatment	Control	3 × 2	114
				180 °C for 1, 2, 3 h	3 × 2 × 2 × 3	
				200 °C for 1, 2, 3 h	3 × 2 × 2 × 3	
				220 °C for 1, 2, 3 h	3 × 2 × 2 × 3	
Hardness	40 (L) × 20 (R) × 20 (T) mm^3 (KS F 2212 (2004))	*Paulownia tomentosa* and *Pinus koraiensis*	Oil and air heat treatment	Control	3 × 2	114
				180 °C for 1, 2, 3 h	3 × 2 × 2 × 3	
				200 °C for 1, 2, 3 h	3 × 2 × 2 × 3	
				220 °C for 1, 2, 3 h	3 × 2 × 2 × 3	

L: longitudinal section, R: radial section, T: tangential section

Table 3 Formulas for physical and mechanical properties

Properties	Formula	Description
Density	$D = m/v$ (g/cm^3)	*m*: the weight of samples *v*: the volume of samples
Volume shrinkage	$VS = 100 \times (V_0 - V_1)/V_0$ (%)	V_0: the volume of samples before heat treatments V_1: the volume of samples after heat treatments
Weight loss in abrasion	$WL = 100 \times (W_0 - W_1)/W_0$ (%)	W_0: the weight of samples before abrasion W_1: the weight of samples after abrasion
Axial compressive strength	$\sigma_{cmax} = P_{max}/A$ (N/mm^2)	P_{max}: maximum load A: compression area
Hardness	$H_c = P/10$ (N/mm^2)	P: load with a press depth of 0.32 mm

with dimensions of 40 (L) × 20 (R) × 20 (T) mm^3 according to KS F 2198 (2016) and KS F 2203 (2004), respectively.

The abrasion, axial compressive strength, and hardness of the wood samples were determined using three specimens with dimensions of 100 (L) × 100 (R) × 10 (T) mm^3, 40 (L) × 20 (R) × 20 (T) mm^3, and 40 (L) × 20 (R) × 20 (T) mm^3 according to KS F 2215 (2006), KS F 2206 (2004), and KS F 2212 (2004), respectively. The abrasion test was performed using a wood abrasion tester (WL120T, Labtron, Ltd., Camberley, UK). The weight loss of the wood before and after abrasion at 100, 200, and 300 rotations for each sample was measured. The axial compressive strength and hardness were evaluated using a universal testing machine (Model 4482, Instron, Norwood, MA, USA). The crosshead speed was 3.0 mm/min for the compressive strength. Hardness was examined by Brinell's method with a 10 mm iron ball in diameter under a crosshead speed of 0.5 mm/min. Hardness tests were performed at six points on every surface of the samples.

2.4 Statistical analysis

The differences in density, volume shrinkage, abrasion, and axial compressive strength between heat treatment methods and among the treatment temperatures and the differences in hardness among the treatment temperatures and durations were statistically analyzed with a univariate analysis of variance. Significant differences were determined using Duncan's multiple range tests (SPSS ver. 24, IBM Corp., New York, USA).

3 Results and discussion

3.1 Physical properties

3.1.1 Density

The densities of *Paulownia tomentosa* and *Pinus koraiensis* wood treated in hot oil and hot air are shown in Figs. 1 and 2, respectively. Oil heat-treated wood from both species

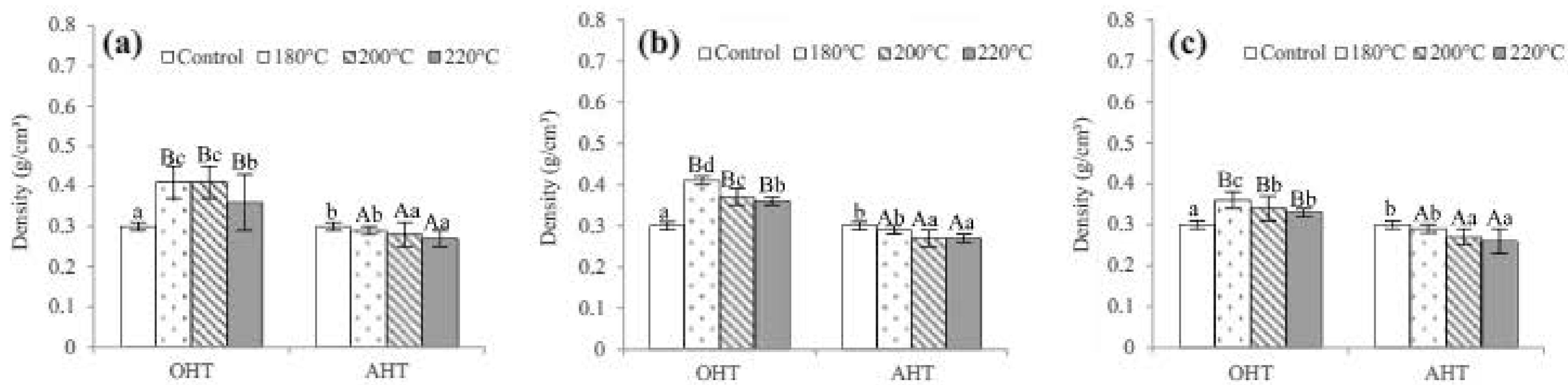

Fig. 1 Effect of temperature and treatment duration on density of *Paulownia tomentosa* in oil (OHT) and air heat treatment (AHT) for 1 (**a**), 2 (**b**), and 3 (**c**) hours. The different capital and lowercase letters above the histogram explain the significant outcomes at 5% level of significance between oil heat treatment and air heat treatment and among treatment temperatures using the Duncan's multiple range tests, respectively

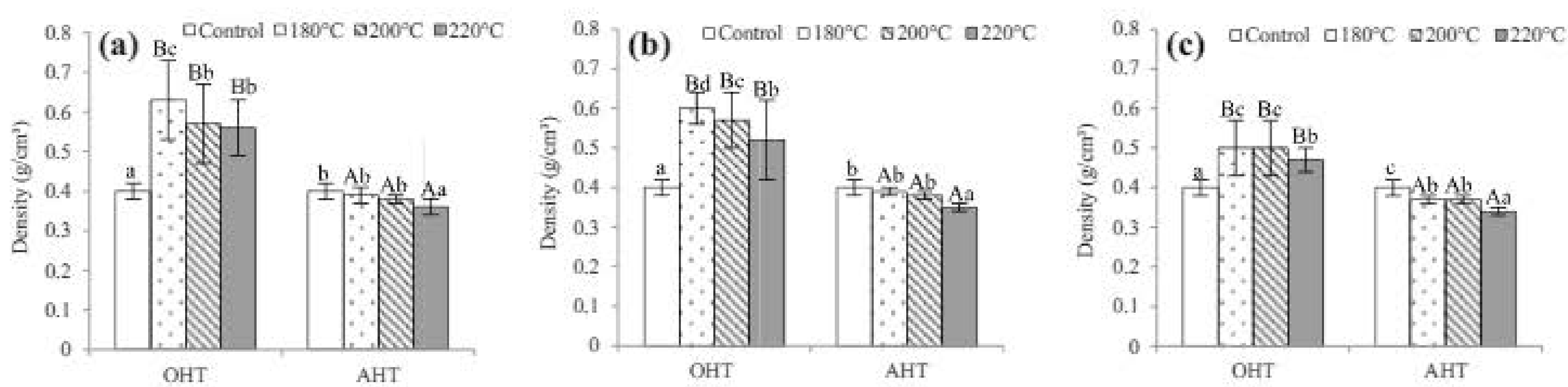

Fig. 2 Effect of temperature and treatment duration on density of *Pinus koraiensis* in oil (OHT) and air heat treatment (AHT) for 1 (**a**), 2 (**b**), and 3 (**c**) hours. The different capital and lowercase letters above the histogram explain the significant outcomes at 5% level of significance between oil heat treatment and air heat treatment and among treatment temperatures using the Duncan's multiple range tests, respectively

showed significantly higher density than air heat-treated wood, mainly due to the oil uptake during treatment. The density was the highest at 180 °C and then decreased slightly at 200 and 220 °C, and decreased significantly after treatment at 200 and 220 °C for 3 h. Dubey et al. (2016) reported that the density of *Pinus radiata* wood by oil heat treatment remarkably increased to approximately 80% higher compared to that of untreated samples. Okon et al. (2018) also observed that the density of oil-heat-treated *Cunninghamia lanceolata* wood increased to 75% in the first stage of treatment due to the oil uptake and decreased gradually as the temperature and treatment duration increased. They explained that the decrease in density is due to the pyrolysis and deterioration of the cell wall polymers during oil heat treatment.

The densities of both wood samples in the air heat treatment significantly decreased. Density decreased significantly after heat treatment at 200 °C in *Paulownia tomentosa* wood and at 220 °C in *Pinus koraiensis* wood. Wang et al. (2014) reported a gradual decrease in the density of *Eucalyptus pellita* wood with increasing temperature from 200 to 240 °C and stated the possible factors for decreasing density during heat treatment: the degradation of hemicellulose and volatile components. Guller (2012) also explained that the decrease in density at higher temperatures might be due to the depolymerization reactions of wood polymers.

3.1.2 Volume shrinkage

Figures 3 and 4 show the volume shrinkage of *Paulownia tomentosa* and *Pinus koraiensis* wood after oil and air heat treatment. The volume of heat-treated wood decreased with both heat treatments. Oil heat-treated *Paulownia tomentosa* and *Pinus koraiensis* woods showed a significantly lower volume shrinkage than air heat-treated wood. With increasing temperature and treatment duration, the volume shrinkage in the oil-heat-treated wood slightly increased. In the air heat treatment, volume shrinkage remarkably increased with increasing temperature and treatment duration. Uribe and Ayala (2015) reported that the shrinkage of heat-treated *Tabebuia rosea, Tectona grandis,* and *Humiriastrum procerum* wood increased with increasing treatment

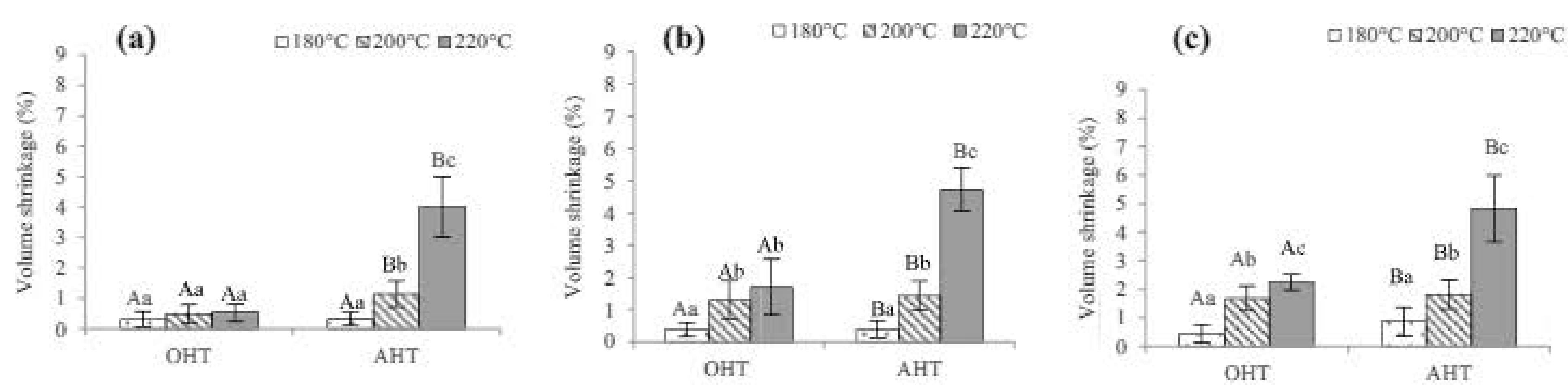

Fig. 3 Effect of temperature and treatment duration on volume shrinkage of *Paulownia tomentosa* after oil (OHT) and air heat treatment (AHT) for 1 (**a**), 2 (**b**), and 3 (**c**) hours. The different capital and lowercase letters above the histogram explain the significant outcomes at 5% level of significance between oil heat treatment and air heat treatment and among treatment temperatures using the Duncan's multiple range tests, respectively

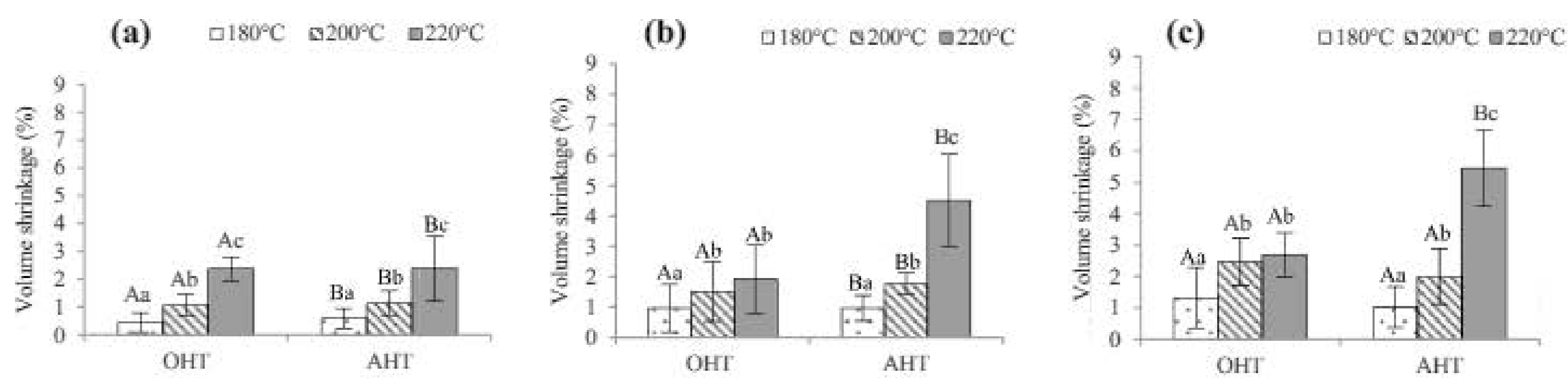

Fig. 4 Effect of temperature and treatment duration on volume shrinkage of *Pinus koraiensis* after oil (OHT) and air heat treatment (AHT) for 1 (**a**), 2 (**b**), and 3 (**c**) hours. The different capital and lowercase letters above the histogram explain the significant outcomes at 5% level of significance between oil heat treatment and air heat treatment and among treatment temperatures using the Duncan's multiple range tests, respectively

temperature. Mazzanti et al. (2012) explained that the volume shrinkage for each species usually exhibited a higher variation after heat treatment at 180 °C. Hidayat et al. (2015) also reported that the increase in volume shrinkage of *Cylicodiscus gabunensis* wood with increasing temperature might be due to the difference in density and volatile extractive content of wood. The shrinkage and swelling values of wood increase with higher density because of the greater amount of thick-walled cells in the wood (Tsoumis 1991).

3.2 Mechanical properties

3.2.1 Abrasion

Table 4 shows the weight loss in the surface abrasion test of *Paulownia tomentosa* and *Pinus koraiensis* wood treated in hot oil and hot air at different temperatures for 2 h. The weight loss of the heat-treated wood samples was significantly higher than that of the untreated samples. With increasing treatment temperature, the weight loss significantly increased in the abrasion test. Thermal treatment can lead to decreased abrasion resistance (Hill 2006). Gong et al. (2010) reported that the air heat-treated *Populus tremuloides* wood showed higher weight loss in the abrasion test than the untreated sample. Chu et al. (2016) reported that in abrasion tests of 100 and 200 rotations, the surface abrasive mass loss value of air-heat-treated *Populus beijingensis* wood increased with increasing treatment temperature, which might be due to the brittle surface of heat-treated wood.

The oil-heat-treated wood samples showed significantly lower weight loss in the surface abrasion test compared to the air-heat-treated samples. It could have been caused by the oil existence in the surface of the oil-heat-treated wood samples, making the surface more slippery and reducing the abrasion process. Oil usually contains a higher linolenic acid that tends to dry quickly and can harden on the surface of the wood after oil heat treatment (Gunstone 2002). Dubey et al. (2010) also explained that linolenic acid protects the oil heat-treated wood surface as a barrier that can protect against external interference. Therefore, oil heat treatment of wood can cause a smaller weight loss than air heat treatment, although the oil-heat-treated wood showed higher weight loss in abrasion than the untreated samples.

3.2.2 Axial compressive strength

The axial compressive strengths of the heat-treated *Paulownia tomentosa* and *Pinus koraiensis* wood are shown in Figs. 5 and 6, respectively. The axial compressive strength of all the samples treated in hot oil and hot air was the highest at 180 °C and then decreased with increasing temperature and treatment duration.

The oil-heat-treated samples showed significantly higher axial compressive strength than the air-heat-treated samples, showing a higher increase in compressive strength in *Pinus koraiensis* than in *Paulownia tomentosa*. The degradation of compressive strength was only observed in *Paulownia tomentosa* wood treated at 220 °C for 3 h. The increase in axial compressive strength after oil heat treatment could be caused by a higher density of oil heat-treated samples and the cell wall thickening and lumen filling by the oil. Bak and Nemeth (2012) reported that *Populus* wood heat-treated in sunflower seed, linseed, and rapeseed oils at 160 and 200 °C for 2, 4, and 6 h showed an increase in compressive strength by 15%–25%. Cheng et al. (2014) reported that compression strength parallel to the grain of *Populus spp.* wood increased after oil heat treatment and explained that the oil may fill the lumen, thicken the cell walls, and provide better lateral

Table 4 Weight loss in surface abrasion test of *Paulownia tomentosa* and *Pinus koraiensis* after oil (OHT) and air (AHT) heat treatment for 2 h

Wood species	Temperature (°C)	Weight loss (%)					
		100 rotations		200 rotations		300 rotations	
		OHT	AHT	OHT	AHT	OHT	AHT
Paulownia tomentosa	Control	0.13 a (0.08)	0.13 a (0.08)	0.33 a (0.18)	0.33 a (0.18)	0.50 a (0.15)	0.50 a (0.15)
	180	0.20 bA (0.07)	0.29 bB (0.03)	0.46 bA (0.11)	0.62 bB (0.13)	0.60 bA (0.13)	0.91 bB (0.15)
	200	0.29 bA (0.08)	0.32 cB (0.06)	0.72 cA (0.09)	0.98 cB (0.06)	0.98 cA (0.06)	1.27 cB (0.14)
	220	0.52 cA (0.23)	0.88 dB (0.14)	0.93 dA (0.22)	1.69 dB (0.22)	1.25 dB (0.42)	2.57 dB (0.47)
Pinus koraiensis	Control	0.05 a (0.01)	0.05 a (0.01)	0.14 a (0.02)	0.14 a (0.02)	0.19 a (0.11)	0.19 a (0.11)
	180	0.13 bA (0.01)	0.26 bB (0.13)	0.24 bA (0.01)	0.58 bB (0.22)	0.26 bA (0.04)	0.92 bB (0.33)
	200	0.16 cA (0.06)	0.75 cB (0.36)	0.30 cA (0.08)	1.34 cB (0.39)	0.40 cA (0.05)	1.91 cB (0.35)
	220	0.17 dA (0.04)	0.78 dB (0.09)	0.31 cA (0.09)	1.68 dB (0.14)	0.40 cA (0.10)	2.61 dB (0.24)

*Numbers in parentheses are standard deviations. The different lowercase and capital letters beside the value explain the significant outcomes at 5% level of significance among treatment temperatures and durations using the Duncan's multiple range tests, respectively

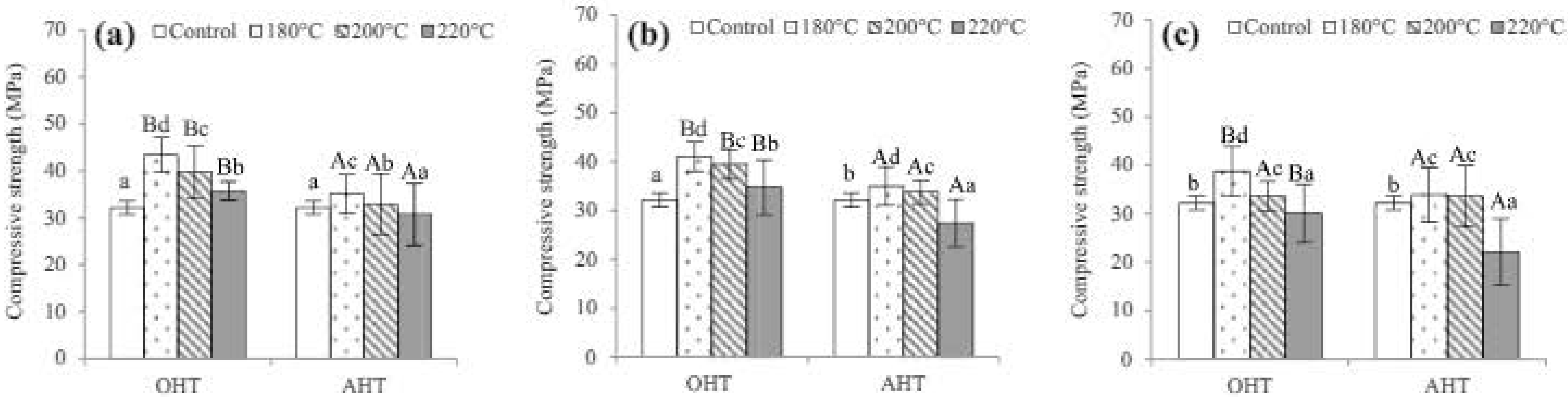

Fig. 5 Effect of temperature and treatment duration on axial compressive strength of *Paulownia tomentosa* after oil (OHT) and air heat treatment (AHT) for 1 (**a**), 2 (**b**), and 3 (**c**) hours. The different capital and lowercase letters above the histogram explain the significant outcomes at 5% level of significance between oil heat treatment and air heat treatment and among treatment temperatures using the Duncan's multiple range tests, respectively

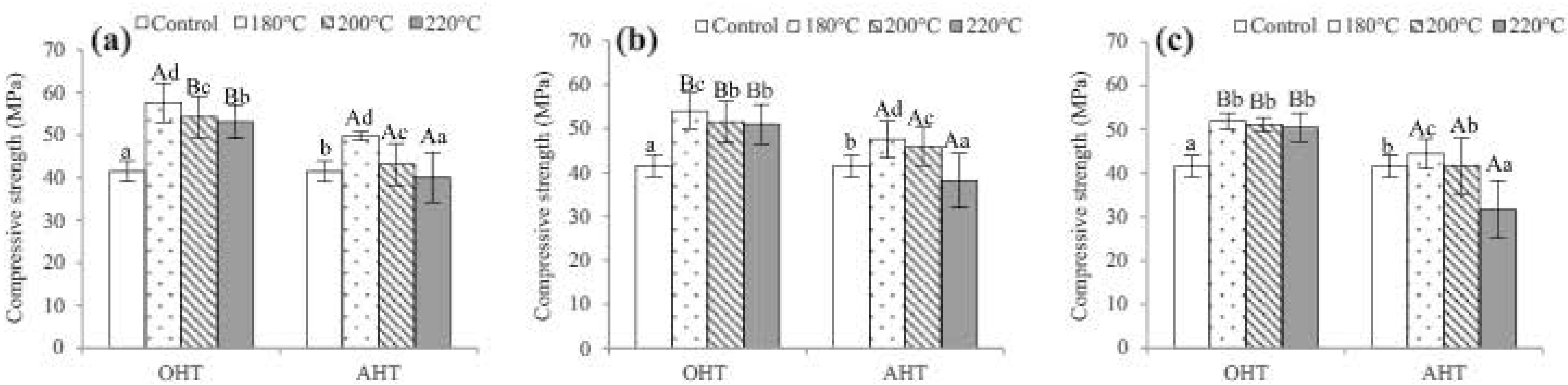

Fig. 6 Effect of temperature and treatment duration on axial compressive strength of *Pinus koraiensis* after oil (OHT) and air heat treatment (AHT) for 1 (**a**), 2 (**b**), and 3 (**c**) hours. The different capital and lowercase letters above the histogram explain the significant outcomes at 5% level of significance level between oil heat treatment and air heat treatment and among treatment temperatures using the Duncan's multiple range tests, respectively

stability to the wood. Tomak et al. (2011) also found that the axial compression strength of oil-heat-treated *Pinus sylvestris* and *Fagus orientalis* wood did not show a significant reduction, mainly due to its high density and high oil absorption in the wood.

In the air heat treatment, the axial compressive strength increased slightly in the temperature range of 180–200 °C and rapidly decreased at 220 °C for each treatment duration. Taghiyari et al. (2013) reported that the compressive strength of air heat-treated *Populus nigra, Populus deltoides*, and *Fagus orientalis* woods increased in the temperature range of 135–185 °C. Bayani et al. (2019) reported that the increased compression strength of air-heat-treated *Fagus orientalis* wood after heat treatment at 145 °C and 165 °C might be due to the increase in the crystallinity of wood. Boonstra et al. (2007b) also reported that the compressive strength of *Pinus sylvestris* wood by air heat treatment increased by approximately 28% after treatment at 165 °C and 185 °C for 90 min. They explained that the increase in compressive strength was probably due to a lower amount of bound water and the increased crystallinity of wood after heat treatment. Regarding the crystalline properties of heat-treated wood, Bhuiyan et al. (2000) and Kim et al. (2018) reported that the relative crystallinity of wood cellulose usually increased after heat treatment. Yildiz et al. (2006) explained the decrease in compression strength parallel to grain in air-heat-treated *Picea orientalis* wood in the temperature range of 150 to 200 °C, mainly due to the degradation of hemicellulose in wood polymers. Therefore, it can be concluded that heat treatment can promote the crystallization of cellulose chains or degrade the crystalline region. The increase in density and crystallinity in the heat-treated wood affects the increase in compressive strength.

3.2.3 Hardness

The hardness values of *Paulownia tomentosa* and *Pinus koraiensis* wood before and after heat treatment are shown in Table 5. There were some differences in hardness due to heat treatment methods, treatment temperature, treatment duration, and wood species.

Table 5 Hardness of *Paulownia tomentosa* and *Pinus koraiensis* after oil and air heat treatment at different temperatures and durations

Wood species	Temperature (°C)	Treatment	Brinell hardness (MPa)								
			Transverse			Radial			Tangential		
			1 h	2 h	3 h	1 h	2 h	3 h	1 h	2 h	3 h
Paulownia tomentosa	Control	Oil-heat treatment	37.10c (4.43)	37.10c (4.43)	37.10c (4.43)	10.89c (2.31)	10.89c (2.31)	10.89d (2.31)	9.90a (2.65)	9.90b (2.65)	9.90c (2.65)
	180		35.79bB (4.01)	34.84bB (4.45)	31.09bA (3.69)	10.63cC (2.78)	9.78bB (2.26)	7.39bA (1.34)	12.51dC (1.84)	11.90 dB (1.52)	9.24cA (2.09)
	200		35.15bB (4.63)	34.14bB (3.78)	29.99aA (4.58)	9.29bB (1.04)	9.25bB (1.67)	6.56aA (1.83)	11.98cC (1.37)	10.87cB (1.68)	8.14bA (1.54)
	220		26.94aA (4.62)	26.90aA (3.61)	26.79aA (4.86)	8.39aB (1.58)	8.29aB (2.30)	6.10aA (2.59)	9.12aC (1.27)	8.06aB (1.09)	6.03aA (2.14)
Pinus koraiensis	Control		44.35a (3.40)	44.35a (3.40)	44.35c (3.40)	14.20b (4.41)	14.20c (4.41)	14.20d (4.41)	12.90a (2.66)	12.90a (2.66)	12.90a (2.66)
	180		54.74dC (2.27)	49.06 dB (2.58)	45.76dA (3.48)	17.88cB (3.88)	12.61bA (1.36)	12.55cA (3.02)	17.80dC (2.75)	16.30 dB (2.04)	15.12cA (2.62)
	200		47.70cB (3.00)	47.61cB (4.39)	43.68bA (5.24)	14.37bB (3.38)	11.91aA (1.48)	11.52bA (1.53)	16.77cC (3.29)	15.42cB (3.91)	13.32bA (2.38)
	220		46.17bB (2.67)	46.73bB (4.00)	39.18aA (2.83)	11.27aB (1.58)	11.45aB (1.63)	9.41aA (1.59)	13.48bB (2.44)	13.26bA (3.83)	13.25bA (3.08)
Paulownia tomentosa	Control	Air-heat treatment	37.10d (4.43)	37.10d (4.43)	37.10d (4.43)	10.89c (2.31)	10.89c (2.31)	10.89d (2.31)	9.90b (2.65)	9.90b (2.65)	9.90c (2.65)
	180		33.28cC (4.11)	31.88cB (4.27)	31.32cA (3.12)	10.20cC (1.56)	8.23aB (1.65)	7.35cA (1.63)	9.68bB (1.36)	9.59bB (2.78)	7.02dA (1.56)
	200		31.06bC (4.23)	29.39bB (4.86)	28.91bA (3.38)	8.38bC (1.86)	7.90aB (1.20)	6.19bA (1.25)	8.78aB (2.29)	8.16aB (1.33)	6.92bA (1.82)
	220		30.48aC (3.79)	27.47aB (4.58)	11.92aA (4.48)	7.73aB (1.40)	7.41aB (1.44)	5.02aA (1.56)	8.26aB (2.04)	8.12aB (0.94)	5.03aA (2.88)
Pinus koraiensis	Control		44.35d (2.07)	44.35d (2.07)	44.35c (2.07)	14.20d (4.41)	14.20d (4.41)	14.20c (4.41)	12.90c (2.66)	12.90c (2.66)	12.90c (2.66)
	180		43.59cB (5.25)	43.49cB (3.20)	42.15bA (1.86)	11.26cB (1.84)	10.64cA (2.29)	10.53bA (0.95)	12.54cB (3.37)	12.68cB (2.98)	10.09bA (0.56)
	200		41.97bB (5.14)	41.27bB (2.05)	36.23aA (2.65)	10.40bC (0.96)	9.24bB (0.87)	8.93bA (0.64)	11.28bB (3.10)	10.22bA (0.64)	10.16bA (1.64)
	220		40.28aC (4.67)	33.79aB (5.20)	32.86aA (4.01)	8.84aC (1.48)	7.05aB (1.02)	6.45aA (1.10)	10.12aC (1.48)	9.94aB (1.54)	5.64aA (1.88)

*Numbers in parentheses are standard deviations. The different lowercase and capital letters beside the value explain the significant outcomes at the 5% significance level among treatment temperatures and durations using the Duncan's multiple range tests, respectively

In the oil heat treatment, the hardness of the transverse and radial surfaces of *Paulownia tomentosa* wood decreased, but in the tangential surface, the hardness of wood treated at 180 and 200 °C for 1 and 2 h slightly increased. The hardness of the transverse and tangential surfaces of *Pinus koraiensis* wood significantly increased at 180, 200, and 220 °C for 1 and 2 h. However, in the radial surface, it increased only at 180 °C for 1 h. Several studies on heat treatment under different atmospheric conditions have shown increased wood hardness. Dubey et al. (2010) mentioned that radiata pine oil heat-treated at 160 °C showed increased hardness in the tangential surfaces by 4.3%. Boruvka et al. (2018) reported that the hardness in the radial and tangential surfaces of air-heat-treated *Betula pendula* wood at 165 and 210 °C increased because of the higher mannan content in hemicelluloses. Boonstra et al. (2007b) found that the Brinell hardness of air-heat-treated *Pinus sylvestris* wood increased by 48% in the transverse surface and by 5% in the perpendicular surface. Sundqvist et al. (2006) reported an increase in the hardness of *Betula pubescens* wood treated at 180 and 200 °C for 1 h and a drastic decrease in hardness after treatment for 2.5 and 4 h. Cao et al. (2012) reported that the hardness of steam-heat-treated *Cunninghamia lanceolata* wood at temperatures below 200 °C increased, and the temperature of 200 °C was a crucial parameter for modifying the mechanical properties of wood. The increase in the hardness of oil heat-treated wood could be caused by a lower amount of bound water and increasing crystalline cellulose and crosslinking of lignin polymer in oil heat-treated wood (Boonstra et al. 2007b; Mohebby et al. 2014).

There are considerably different results in the hardness of the air-heat-treated samples. In both air-heat-treated *Paulownia tomentosa* and *Pinus koraiensis* wood, the hardness on the transverse, radial, and tangential surfaces decreased significantly with increasing temperature and treatment duration, as shown in Table 5. Several studies on the hardness of air-heat-treated wood support these results. Gunduz et al. (2008) reported a decrease in the hardness of *Pinus nigra* wood treated in the temperature range of 120–180 °C for 2–10 h. Korkut and Hiziroglu (2009) also reported that the hardness of air-heat-treated *Corylus colurna* wood on the three surfaces decreased with increasing treatment temperature and duration. Reinprecht and Vidholdová (2008) reported that the hardness decreased by 1.5% in *Fagus sylvatica* wood treated in rapeseed oil at 180, 200, and 220 °C for 3 to 6 h. Bakar et al. (2013) reported that the hardness of air-heat-treated *Quercus rubra*, *Juniperus virginiana*, and *Hevea brasiliensis* wood decreased gradually as the temperature and treatment duration increased. They explained that the decrease in hardness is possibly due to the oxidation reaction and degradation of hemicellulose in wood.

4 Conclusion

The physical and mechanical properties of heat-treated wood in air and oil were examined and compared. There were significantly different values in the physical and mechanical properties between oil and air heat treatments and among treatment temperatures and durations. The density of both wood samples was significantly increased by oil heat treatment and vice versa by air heat treatment. Oil heat-treated wood samples showed lower volume shrinkage and weight loss in abrasion than air heat-treated samples, and with increasing treatment temperature, the volume shrinkage and weight loss increased in both heat treatments. The axial compressive strength of all the samples treated in hot oil and hot air was the highest at 180 °C and then decreased with increasing temperature and treatment duration. The hardness of oil-heat-treated *Pinus koraiensis* wood increased but decreased in oil heat-treated *Paulownia tomentosa* wood and both air-heat-treated woods.

In conclusion, *Paulownia tomentosa* and *Pinus koraiensis* wood heat-treated in oil exhibited relatively better physical and mechanical properties than those heat-treated in air. Therefore, it can be suggested that oil heat treatment is a more effective method to improve some physical and mechanical properties of wood compared to air heat treatment.

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