Effects of Thermal Treatment on Air-dried Density, Color Change, Average Surface Roughness, and Sound Absorption Capacity of Scots Pine

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This study was conducted to investigate some characteristics of thermally treated Scots pine (*Pinus sylvestris* L.) wood specimens such as air-dried density, color change, average surface roughness, and sound absorption capacity. Heat treatment of Scots pine wood was performed at atmospheric pressure at 140, 160, 180, and 200 °C for 2 h. As a result, the air-dried density values of the thermally treated wood decreased as the temperature of the thermal treatment increased. With the increase of thermal treatment temperature, an increase in total color change values was detected on the surfaces of the samples and the color of the samples became darker. The average surface roughness (R_a) value of samples improved due to thermal treatment conditions and the highest value was determined in thermally treated samples at 200 °C as 3.59 µm. At 140 °C the value of maximum sound absorption coefficient was observed to be 0.48 at 2500 Hz and the highest sound transmission loss value, which was 36.7 dB, was measured at 6300 Hz and at 200 °C.

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INTRODUCTION

Wood has been one of the most used building and construction materials since the beginning of human civilization. Wood is a natural, sustainable, hygroscopic, and anisotropic material. The properties, such as renewable, thermal, acoustic, electrical, mechanical, aesthetic appearance, ease of working, improving health and happiness, cost-effective, *etc*., make wood an extremely suitable material for the construction industry. However, because wood is a natural material, it can be easily degraded by various biotic and abiotic factors such as termites, insects, fungi, moisture, fire *etc*. In an effort to overcome weak and negative properties of the wood material, to improve its existing properties, and with increasing the demand for wood material with good properties, there have been accelerated efforts to improve the properties of wood (Rowell 2012; Ramage *et al.* 2017; Sandberg *et al.* 2017). Wood modification is essentially applied to overcome some weak and undesirable properties of wood, such as low resistance to bio-deterioration, low dimensional stability, low hardness and wear resistance, low resistance to weathering, hygroscopic properties, and to improve aesthetic properties (Hill 2006; Jones and Sandberg 2019; Pelit and Yorulmaz 2024).

The thermal modification of wood has been generally accepted as an effective and environmentally friendly method with no additional wood preservative chemicals; it is a well-established commercial modification technology for improving the dimensional stability and durability of wood (Gaff *et al.* 2019; Sandberg *et al.* 2021). In the thermal treatment process, wood is generally heated to temperatures ranging from 160 to 260 °C, where lower temperatures cause a slight change in wood properties, while higher temperatures cause radical chemical changes of the basic components of wood (Hill 2006; Esteves and Pereira 2009). Thermal modification causes changes in the structure of wood cell wall polymers (cellulose, hemicelluloses, and lignin), which is reflected in a change in its hygroscopicity, dimensional stability, permeability, and decay resistance in wood properties (Boonstra 2016). Metsa-Kortelainen *et al.* (2006) reported that the thermally treated Scots pine (*Pinus sylvestris*) and Norway spruce (*Picea abies*) heartwood at 170, 190, 210, and 230 °C for 3 h evidently decreased the water absorption, which was influenced by an increase in temperature. Esteves *et al.* (2014) studied the effect of thermal treatment at 190 and 200 °C for 2 to 6 h on the equilibrium moisture content (EMC) and antishrinking efficiency on sapwood and heartwood samples of pine (*Pinus pinaster* Ait.). The results showed that the EMC decreased approximately 39% to 42% and the anti-shrinking efficiency increased approximately 50%, in relation to untreated wood. In another study, Boonstra *et al.* (2007) studied that the effect of thermal treatment process (under relatively mild conditions < 200 °C) on the resistance against fungal attacks. Test samples were prepared from radiata pine (*Pinus radiata D.*), Scots pine (*Pinus sylvestris* L.), Norway spruce (*Picea abies* Karst), and Birch (*Betula pendula* and/or *Betula pubescens*) woods. Test results showed that a thermal treatment process protects wood material against fungal attacks.

Color change occurs in the wood material after thermal treatment. Such color may be found more attractive and preferred by different customers; therefore, color change may become an important factor in purchasing processes of wood (Brischke *et al.* 2007). It is a well-known fact that color darkening is greater especially at high temperatures (Chen *et al.* 2012). Esteves *et al.* (2007) found that pine (*Pinus pinaster*) and eucalyptus (*Eucalyptus globulus*) wood became darker, with the lightness decreased related to chemical changes by 50% following thermal treatment with hot air or steam over a period of 2 h to 24 h above 170 °C. Additionally, Esteves *et al.* (2007) reported that color may be important in influencing the consumer's preferences in terms of visual appearance and aesthetics in the selection of wood materials, as well as providing an alternative solution to the use of tropical wood species.

Hardness in wood materials is often an important mechanical property that is directly related to other mechanical properties (Li *et al.* 2017). Poncsak *et al.* (2006) conducted research with heat-treated birch (*Betula papyrifera*) and showed that hardness increases slightly with temperature, especially above 200 °C, while Korkut *et al.* (2008) concluded that Janka-hardness decreased with thermal treatment for Scots pine (*Pinus sylvestris* L.) and maximum hardness loss was obtained for treated samples at 180 °C for 10 h.

Thermally treated wood is characterized by increased fragility, as well as reduced mechanical strength; for this reason it is not suitable for structural applications, while it is commonly used for non-load-bearing applications, such as decking, siding, flooring, wall paneling, ceilings, accent walls, and even doors and other outdoor/indoor applications (Jirouš-Rajković and Miklečić 2019; Nhacila *et al.* 2020; Ali *et al.* 2021).

Bekhta and Niemz (2003) reported that both bending strength and modulus of elasticity of Spruce wood (*Picea abies*) decreased when the thermal treatment temperature was more than 100 °C, and a 50% decrease in bending strength was observed for the samples treated at 200 °C.

Thermal conductivity and acoustic performance of wood material are important properties in interior applications (Caniato *et al.* 2021) and the properties of wood materials play an important role in the auditory stimulation of sound and sound quality in interior spaces (Çavuş and Kara 2020). The acoustic performance of wood material is affected by its formation, surface treatments, assembly processes, and geometric properties (Bucur 2023). Vasubsbu *et al.* (2015) studied the thermal conductivity of several wood samples, and they reported that the lowest thermal conductivity was obtained for the most porous woods. In addition, Çavuş *et al.* (2019) studied that thermal conductivity properties of some wood material and they reported that thermal conductivity performance varies depending on the type and density of the wood material and that there is a linear relationship between density and thermal permeability. Chung *et al.* (2017) determined that the sound absorption coefficient increased with the treatment temperature and treatment time. Jang and Kang (2021) determined that the sound absorption effect of the radial plane was negligible and found that thermally modified Indonesian *Homalium foetidum* would be expected to absorb sound when used in cross-section. Mania and Gąsiorek (2020) determined that the acoustic parameters improved after oil-heat treatment (OHT). Bertoloni *et al.* (2019) determined that panels with more porosity are more acoustically efficient with a sound absorption coefficient close to 0.8 at 3.2 kHz and show better thermal conductivity performance.

Wood is one of the most important materials widely used in interior decoration, furniture, and decoration elements due to its superior properties (Alapieti *et al.* 2020; Saka and Kahraman 2020; Uzun and Sarıkahya 2021; Yeşil *et al.* 2021). Moreover, due to the advantages of heat-treated materials, the usage area, user demand, and market volume continues to increase (Jirouš-Rajković and Miklečić 2019; Jones *et al.* 2019).

Most previous studies have focused on the influence of thermal treatment on the mechanical properties, dimensional stability, and color of Scots pine (*Pinus sylvestris* L.) wood (Korkut *et al.* 2008; Durmaz *et al.* 2019; Yıldız and Gürgen 2021; Piernik *et al.* 2022), but there have been fewer studies assessing acoustic and thermal performances of Scots pine (*Pinus sylvestris* L.). Determining the physical properties of wood material (density, surface roughness, color changes, acoustic performance, *etc.*) and knowing these properties well makes its use in interior and exterior decoration applications efficient.

Therefore, this study aims to provide more information on the physical properties of thermally treated Scots pine (*Pinus sylvestris* L.) wood, including air-dried density, color changes, average surface roughness, and sound absorption capacity.

EXPERIMENTAL

Material and Method

Scots pine (*Pinus sylvestris* L.) wood specimens were preferred as the test materials in this study, because of their common usage in the wood industry. Scots pine timber (approximately 14% of moisture content) free of defects was randomly obtained from a sawmill in the Kütahya Province in Turkey.

The test samples were prepared in compliance with ISO 3129 (2019) from regular woods, void of roots and knots, and the samples were randomly chosen from first class timbers, without color differences or density variations.

Scots pine planks dimensions of 120 mm× 25 mm × 450 mm (tangential × radial × longitudinal) were kept in a climate chamber (Nüve ID 501) under the relative humidity of 65% ± 5% and a temperature of 20 ± 2 °C for 5 weeks before thermal treatment. The planks were prepared sufficiently for each experimental group and were divided into five groups. The first group served as a reference (control) and was not thermally treated. The remaining four groups were thermally treated at atmospheric pressure using temperatures of 140, 160, 180, and 200 °C for 2 h. Heat treatment was applied to the samples under atmospheric pressure in the laboratory high-temperature chamber (Nüve FN 120). The thermally treated test specimens were then re-conditioned to stabilize EMC in an environment with a relative humidity of 65% ± 5% and a temperature of 20 ± 2 °C.

Subsequently, test samples were prepared from these planks according to the relevant standards. The preparation of the density test specimens was based on ISO 13061-2 (2014). The sample size was 30 mm × 20 mm × 20 mm (longitudinal × radial × tangential) (Fig. 1). For air-dried density, test samples were stored in the conditioning cabin, with a temperature of 20 ± 2 °C and relative humidity of 65% ± 5%, until they reached a stable weight. Ten replicates were used for each treatment condition of temperature.

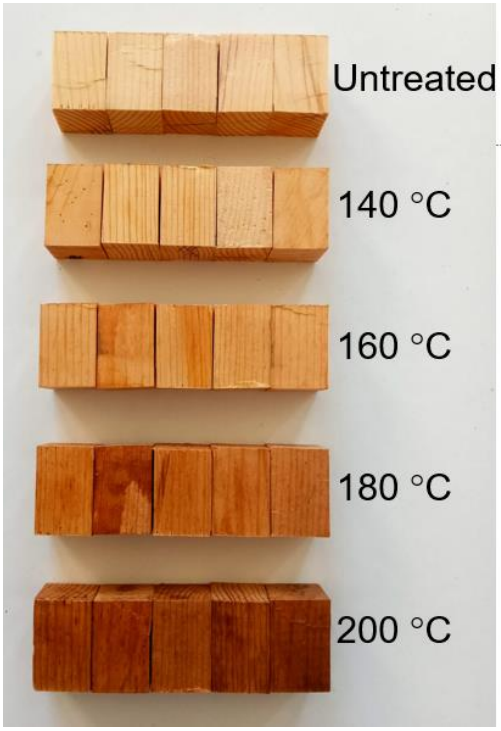

Fig. 1. Untreated and thermally treated Scots pine samples

After the necessary measuring and weighing procedures, the air-dry density value was calculated as follows:

$$D_{12} = W_{12} / V_{12} \text{ (g/cm}^3\text{)} \quad (1)$$

where D_{12} denotes air-dried density (g/cm^3), W_{12} is air-dried weight (g), and V_{12} is air-dried volume (cm^3).

The color (CIE $L^*a^*b^*$) of wood specimens caused by heat treatment in all experiments were measured with the color meter (Color striker) (Fig. 2) according to the principles specified in ISO 11664-4 (2019), in only the tangential surface. The sample size used was 100 mm × 20 mm × 100 mm (longitudinal × radial × tangential). The tangential surface was chosen because it is more common in actual practical usage (Borůvka *et al.* 2021). The L^* represents the black-and-white axis, from perfect black ($L^* = 0$) to perfect white ($L^* = 100$), a^* value represents red and green opponents at positive and negative values, respectively, while b^* value represents yellow and blue opponents at positive and negative values, respectively. Measurements were replicated ten times for each treatment condition. The L^*, a^*, and b^* values were used to calculate the color changes ΔL^*, Δa^*, and Δb^*. Subsequently, the total color change (ΔE^*) was calculated using Eq. 2,

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

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

where the subscript "i" indicates the initial value before treatment and "f" describes the final value after treatment.

Fig. 2. Color striker

The average surface roughness parameters (R_a) were evaluated based on the ISO 4287 (1997) standard. The sample size was 100 mm × 20 mm × 100 mm (longitudinal × radial × tangential), because the average roughness parameter is the most used parameter for surface roughness measurements (Aydın and Çolakoğlu 2003). Surface roughness parameter (R_a) of test samples was determined using a touch scan (spined) surface roughness tester (TIME TR 200) (Fig. 3). Fifteen replicates were used for each treatment condition of temperature.

Fig. 3. Surface roughness measurement device

The sound absorption properties of the thermally treated and untreated samples were quantified according to the ISO 10534-2 (1998) standard, using impedance tubes (Fig. 4) of type BSWA-SW422-540017 (Şiteks company, Tekirdağ, Turkey). The measuring range was 63 to 1600 Hz for samples with a diameter of 100 mm and thickness of 20 mm, and 1600 to 6300 Hz for samples with a diameter of 29 mm × thickness of 20 mm. Sound transmission loss in the frequency range of 50 to 6300 Hz was measured using impedance tubes. In addition, an impedances tube of 29 mm diameter was used for measuring sound transmission loss. The transmission loss was measured in the frequency range of 50 to 6300 Hz under temperature of 20 °C, humidity 50%, and 1013 hPa. Three replicates were used for each treatment condition of temperature.

Fig. 4. Impedance tubes and test samples

Porosity and density of wood are important properties that have a significant effect on material properties such as flow, adsorption, impregnability, heat conductivity and tensile and bending strength (Plötze and Niemz 2011). One of the most important aspects of sound absorbing materials is their structure, either fibrous or porous, and also internal voids in wood materials may have effects on sound absorption coefficients (Bertolini *et al.* 2019). The porosity of the test samples was determined according to the following formula stated by Varivodina *et al.* (2010),

$$P = [1-(D_0 / 1.53) \text{ x } 100] \quad (4)$$

where P is the porosity of wood (%) and D_0 is the density of the dry specimens (g/cm^3).

Statistical Analyses

The experimental data were analyzed by using the MSTAT-C software package (Version 1.42, Michigan State University, USA) with the analysis of variance (ANOVA). Significant differences between mean values of the parameters describing the properties of samples were determined by using Duncan's multiple range test. Comparisons were considered significant at $P \leq 0.05$.

RESULTS AND DISCUSSION

The mean of air-dry density, color parameter for a^*, b^*, L^*, total color change (ΔE^*), standard deviation values, and homogeneity groups of the thermally treated and untreated (control) samples are given in Table 1. Results indicate that density values decreased with the increasing temperature and the highest losses in density were realized at 200 °C. Control specimens had an average air-dry density of 0.518 g/cm^3, and this value was reduced 3%, 6.6%, 7.3%, and 11.8% as a result of heat exposure at temperature levels of

140, 160, 180, and 200 °C, respectively. Degradation of hemicellulose into volatile substances and evaporation of extractives are the primary parameters responsible for the density reduction of wood when thermally treated (Esteves and Pereira 2009). Further, it can be said that the decreases in the EMC and mass losses of the test samples are important factors in the decrease of air-dry density values after thermal treatment (Pelit and Yorulmaz 2019). Previous studies also reported that a loss in the density values of Scots pine depends on thermal treatment conditions (Korkut and Bektas 2008; Durmaz *et al.* 2019; Demirel and Sen Er 2022). The results of the present study are in accordance with the results available in the literature. The values of air-dried density are given in Fig. 5.

Table 1. Mean, Standard Deviation and Homogeneity Groups of Test Samples for Density, *a**, *b**, *L**, Δ*E** and Surface Roughness

Thermal Treatment	Density (g/cm^3)	*a**	*b**	*L**	Δ*E**	Surface Roughness (µm)
Control	0.518^{A} (0.0082)	3.59^{C} (0.2065)	13.68^{D} (0.1543)	20.57^{A} (0.4502)	-	2.78^{D} (0.0763)
140 °C	0.502^{B} (0.0076)	3.59^{C} (0.1326)	14.36^{C} (0.3098)	19.72^{B} (0.5634)	1.24^{D} (0.5934)	3.23^{B} (0.1667)
160 °C	0.484^{C} (0.0286)	3.74^{C} (0.4139)	14.80^{B} (0.5456)	19.55^{B} (0.4075)	1.94^{C} (0.7441)	3.05^{C} (0.1453)
180 °C	0.480^{D} (0.0183)	4.05^{B} (0.2977)	15.16^{AB} (0.3999)	17.68^{C} (0.4288)	3.32^{B} (0.5268)	3.25^{B} (0.1735)
200 °C	0.457^{E} (0.0221)	4.33^{A} (0.1571)	15.37^{A} (0.3656)	15.61^{D} (0.7821)	5.33^{A} (0.7696)	3.59^{A} (0.1405)

Homogeneity groups: The same letters in each column indicate that there is no statistical difference between the samples according to the Duncan's multiple range test. Numbers in parenthesis are standard deviations. Means are the average of 10 replications and 15 replications for surface roughness.

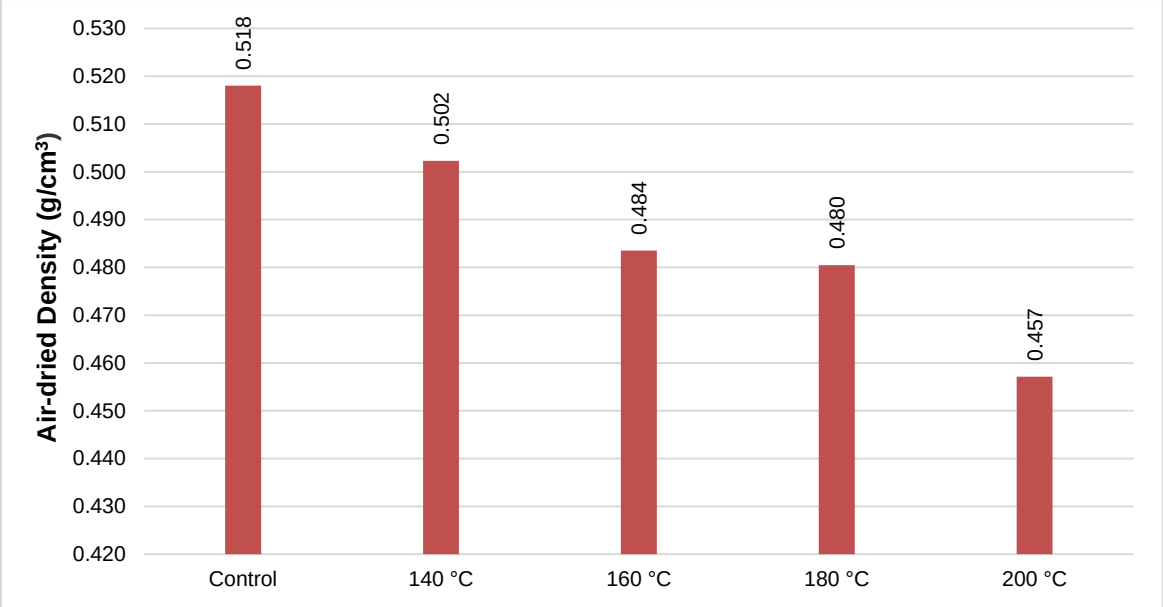

Fig. 5. Density values of thermally treated wood samples

The results of the color parameters for thermally treated and untreated test samples are shown (a^*, b^*, and L^*) in Fig. 6, color changes (Δa^*, Δb^*, and ΔL^*) in Fig. 7, and total color changes (ΔE) in Fig. 8.

The color measurements in Fig. 6 show that the color values for the different temperatures represented a clear effect of temperature on color changes. When visually examined, the original light color of Scots pine wood samples turned dark brown after thermal treatment. While a^* and b^* color values slightly increased depending on the temperature, the L^* values decreased as the temperature increased and the lowest was found at 200 °C.

While the chromaticity coordinates ($\Delta a^*$and Δb^*) showed a slight increase after thermal treatment, the ΔL^* resulted in negative values (Fig. 7). This means that the wood had become darker after thermal treatment. Darkness increased with the increase in temperature from 160 to 200 °C, and it was more intense at 200 °C. The maximum difference in the lightness value (ΔL^*) for the thermally treated wood was determined as -4.96 in the samples treated at 200 °C, and the minimum as -0.85 in those treated at 140 °C. The minimum difference in the red color value was found as 0.05 in the samples subjected to thermal treatment at 140 °C and the maximum as 0.74 in those treated at 200 °C.

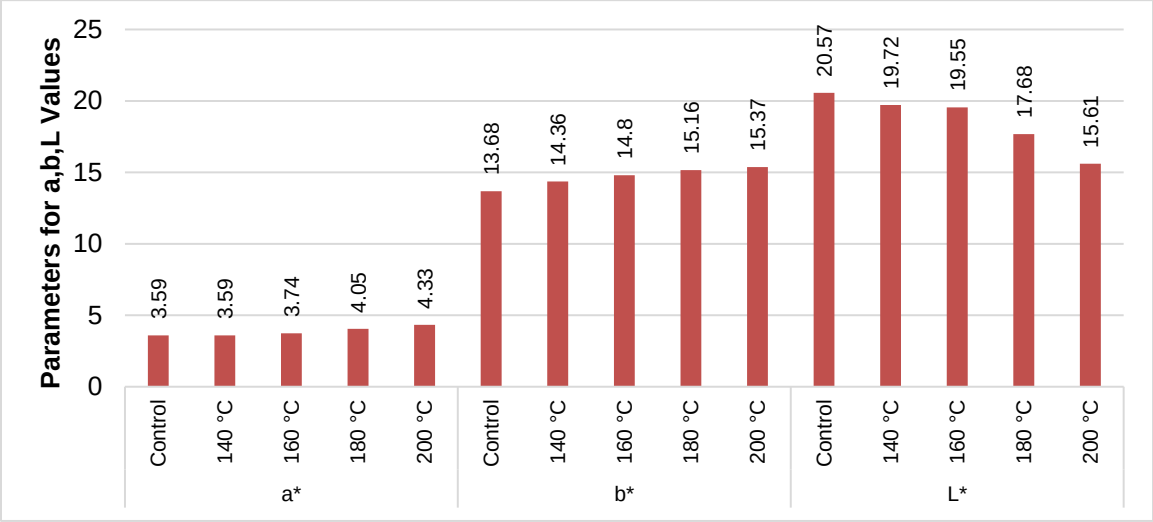

Fig. 6. Color measurement values for a^*, b^*, and L^* of test samples

In Fig. 7, the maximum difference in the yellow color value (Δb^*) was determined as 1.68 in the samples thermally treated at 200 °C, and the minimum as 0.68 in those treated at 140 °C. Bekhta and Niemz (2003) reported that thermal treatment temperature above 150 °C affects all color parameters.

According to Fig. 8, the maximum total color change value (ΔE^*) of the samples was obtained as 5.33 in the samples thermally treated at 200 °C, and the minimum as 1.24 in those treated at 140 °C. The decrease in lightness (ΔL^*) resulting in total color difference (ΔE^*) and accelerated darkening when heat treatment exceeded 200 °C was previously reported for Scots pine by Kucuktuvek *et al.* (2017) and Durmaz *et al.* (2019). Tomak *et al.* (2014) reported that the yellow color value of Scots pine increased after thermal treatment and they also emphasized that reddish (Δa^*) and darker ($-\Delta L^*$) color after thermal treatment could be due to cause by formation of secondary products in the wood material

as a result of the thermal treatment and decomposition due to the release of quinone and quinone methide. According to Mitsui *et al.* (2001) changes in the structure of lignin and hemicellulose during thermal treatment are the reasons for color changes. Gonzales-Pena and Hale (2009) reported that color change (ΔE^*) was highly influenced by the lightness parameters (ΔL^*) and also suggested that ΔE^* in thermally treated wood originated from the chemical changes in the wood polymers, especially more in lignin than in polysaccharides.

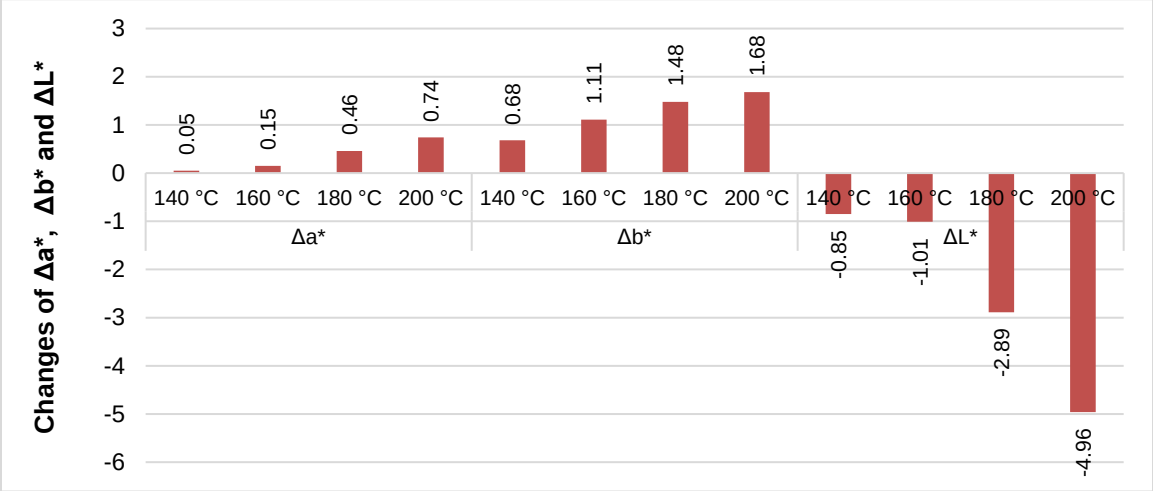

Fig. 7. Color variation of thermally treated samples

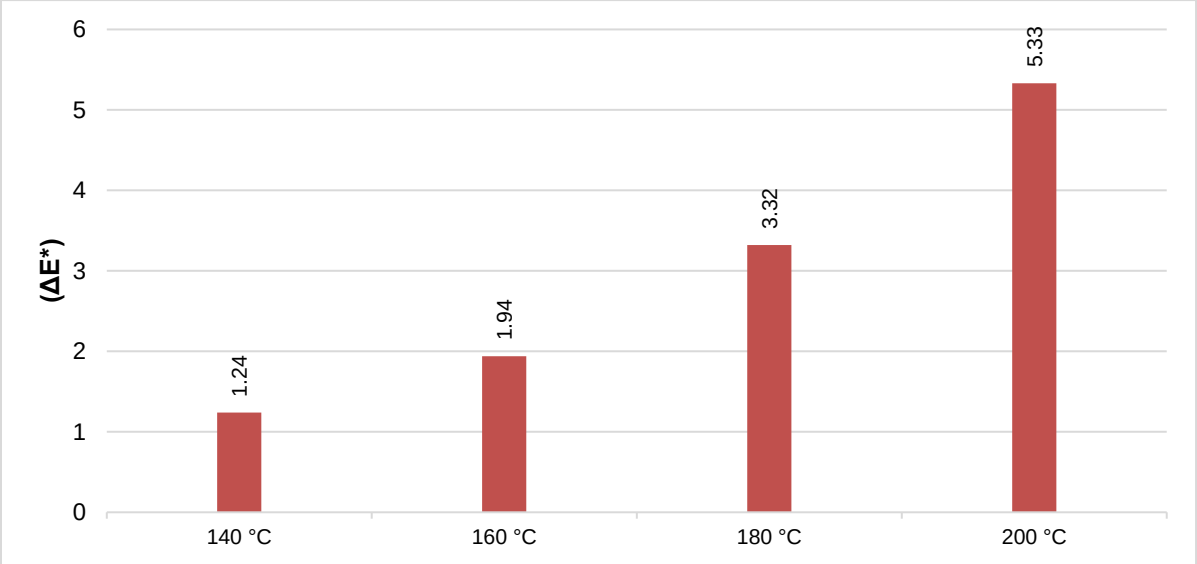

Fig. 8. Total color changes of thermally treated samples

The average surface roughness (R_a) values of wood samples are presented in Fig. 9. The results showed that the thermal treatment increased the surface roughness of samples. The highest surface roughness value (3.59 µm) was obtained in thermally treated samples at 200 °C. Surface roughness parameters increased depending on the increase of treatment conditions. Control specimens had an average surface roughness of 2.78 µm, and this value was increased 16%, 10%, 17%, and 29% as a result of heat exposure at

temperature levels of 140, 160, 180 and 200 °C, respectively. In the literature, it was expressed that surface roughness values increased with increasing thermal treatment temperature, and that chemical changes caused by thermal treatment, especially those associated with hemicellulose changes, caused an increase in surface roughness (Budakçı *et al.* 2013). Additionally, in the study conducted by Pelit *et al.* (2015), it was reported that the surface roughness values of Scots pine samples increased depending on the heat treatment temperature. Average surface roughness (R_a) values of the thermally treated Scots pine wood were higher than control samples before weathering (Kucuktuvek *et al.* 2017). In contrast, the surface roughness values obtained from this study contrast with some previous studies (Pinkowski *et al.* 2016; Ayata *et al.* 2018; Durmaz *et al.* 2019). It is considered that this situation is due to the applied thermal treatment conditions.

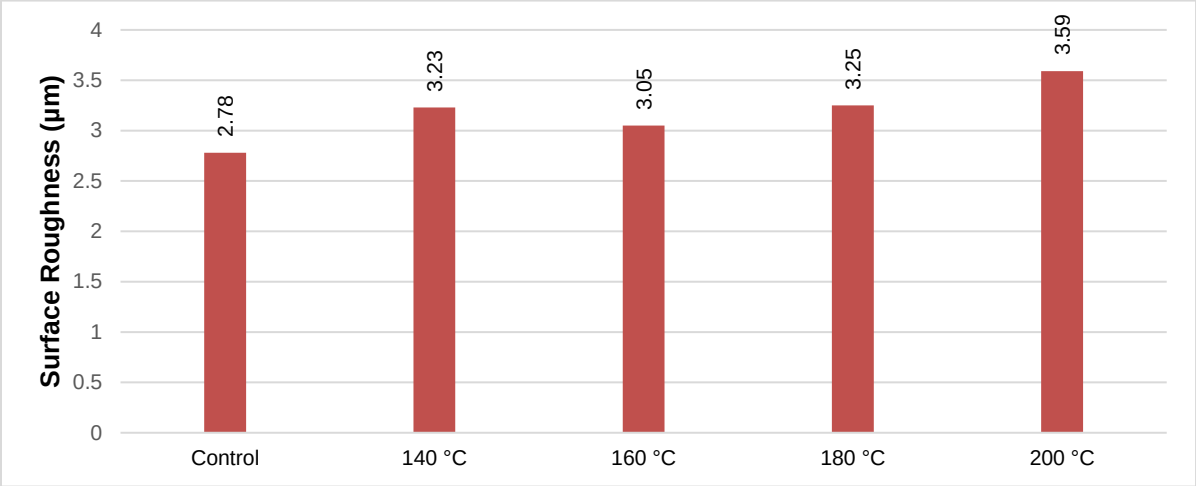

Fig. 9. The surface roughness values of thermally treated Scots pine

Sound absorption coefficient (SAC) values measured in the 63 to 6300 Hz frequency range of control and thermally treated samples are given in Fig. 10.

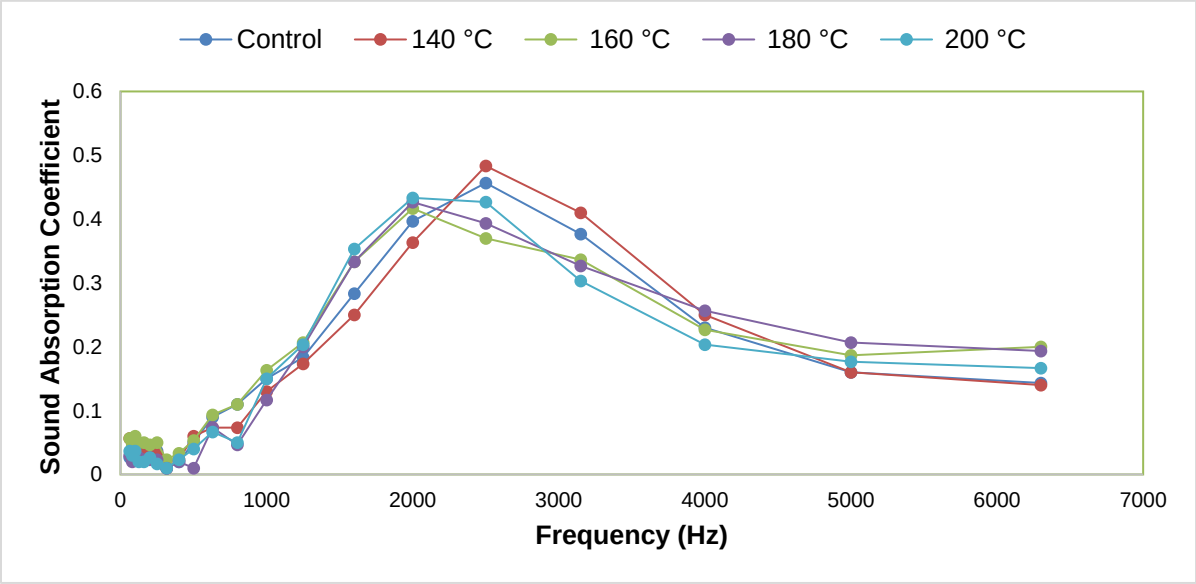

Fig. 10. Sound absorption coefficients of test samples

As shown, the increase in the rate of SAC was in the 2000 to 3000 frequency band range compared with the low-frequency band range. The SAC values of control and thermally treated samples tend to decrease in the high frequency region. When generally evaluated, according to Fig. 10, the SAC value peaked at 2500 frequency at 140 °C was 0.48. In contrast, at low frequencies, the SAC values of control and then thermally-treated samples are very similar.

Sound absorption coefficients of the test samples also changed depending on the heat treatment temperature and frequency values. The SAC changed from 0.01 at 315 Hz to 0.48 at 2500 Hz after thermal treatment at 140 °C. When thermally treated at 160 °C, the SAC changed from 0.02 at 315 Hz to 0.41 at 2000 Hz; when thermally treated at 180 °C, it changed from 0.01 at 315 Hz to 0.42 at 2000 Hz, and at 200 °C it changed from 0.01 at 315 Hz to 0.43 at 2000 Hz. Kang *et al.* (2018) studied sound absorption capability and air permeability of thermally modified Malas (*Homalium foetidum*) wood. They reported that noise reduction coefficients of *Homalium foetidum* specimens were 17% for treated and 10% for control samples. The mean of SAC of specimens in the frequency range of 50 to 6400 Hz were 42% for treatment and 17% for control samples, respectively. Sound absorption properties were also improved by thermal treatment (Byeon *et al.* 2010). Chung *et al.* (2017) reported that the porosity value of the wood material increased depending on thermal treatment temperature, and this caused an increase in the SAC in the high frequency band range.

The determined transmission loss of control and thermally modified samples are presented in Fig. 11. As shown in Fig. 11, the transmission loss values increased with the thermal treatment except for 140 °C. At frequencies higher than 1250 Hz, the average values of sound transmission loss of thermally treated samples at 180 and 200 °C were similar. As shown in Fig. 11, the sound transmission loss values of treated specimens at 140 °C showed lower values than those of control specimens in almost all frequency ranges. When the average values were considered, the highest sound transmission loss value was measured as 36.7 at 6300 Hz, and at 200 °C. Moreover, as frequency increased, sound transmission loss values tended to increase at 160, 180, and 200 °C.

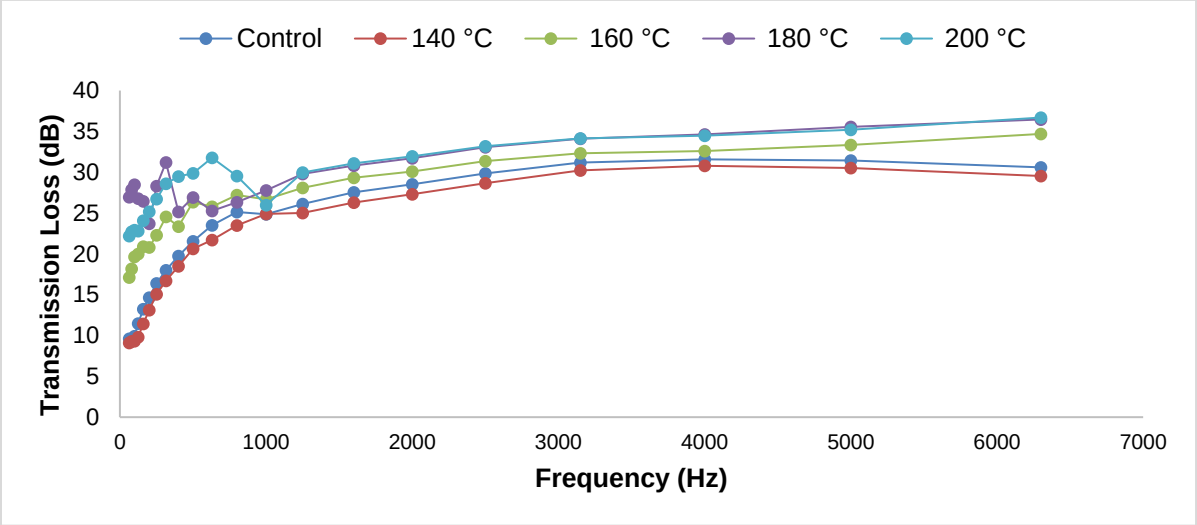

Fig. 11. Sound transmission loss of test samples

Heat treatment caused depolymerizations in hemicellulose, cellulose, lignin, and extractives in the wood cell wall (Cheng *et al.* 2016). Solid substances within the wood material decreased due to thermal treatment condition, and there were increases in the pores and the amount of through-pore porosity (Chung *et al.* 2017; Jang and Kang 2019; Mawardi *et al.* 2022). Kaya (2023) reported that as porosity increased, average sound transmission loss values of thermally treated Mediterranean cypress and field maple wood samples increased 86% and 32%, respectively. In a similar study conducted by Kang *et al.* (2019), it has been reported that the sound transmission loss of thermally treated with high-porosity *Paulownia tomentosa* wood is on average 30 to 40 and 36.93 dB at 50 to 6400 Hz. Porosity values of the thermally-treated and untreated samples are given in Table 2.

Table 2. Porosity of the Thermally-Treated and Untreated Samples

	Control	140 °C	160 °C	180 °C	200 °C
Mean (g/cm^3)	66.12	67.20	68.39	68.60	70.14
Min (g/cm^3)	65.40	66.30	65.95	66.29	67.92
Max (g/cm^3)	66.97	67.89	71.13	70.65	71.90
N	10	10	10	10	10
SD	0.52	0.38	1.71	0.88	1.37
N: Number of test specimens, Mean: Average of 10 replicates, Min: Minimum value, Max: Maximum value, SD: Standard deviation					

According to Table 2, as the heat treatment temperature increased, the porosity of the test samples increased. The highest porosity value was determined in the test samples heat-treated at 200 °C as 74.1%. The porosity increased by approximately 6% compared to the control samples at the highest temperature. Drying wood material at high temperature can affect the porosity of the wood. High temperature causes thermal degradation of wood components, which can lead to the formation of voids within the cell wall. The removal of hemicellulose and lignin during heat treatment creates new pores in the fiber cell wall. As water leaves the pores during drying, the pore walls begin to collapse, eventually resulting in pore closure by irreversible hydrogen bonding. Additionally, anisotropic drying shrinkage of cell wall layers causes internal drying stresses that can be large enough to damage wood cell walls (Borrega and Kärenlampi 2011). It was also reported that drying of wood may result in an increase of the material porosity, especially after delignification process, as investigated by Vitas *et al.* (2019).

CONCLUSIONS

1. As the treatment temperature increased, the red and yellow colors slightly increased, and the darkness increased with the increase in temperature. Additionally, the maximum total color change value of the samples was achieved in samples thermally treated at 200 °C.
2. The average surface roughness (R_a) value of samples increased due to thermal treatment conditions and the highest R_a value was obtained in thermally-treated samples at 200 °C.

3. Sound absorption coefficients of the test samples also changed depending on the thermal treatment temperature and frequency values. In addition, the SAC value peaked at 2500 frequency at 140 °C as 0.48. The transmission loss values increased with the thermal treatment except for 140 °C.

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