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Thermal treatment of wood alters its structure due to degradation of wood polymers (cellulose, hemicellulose, and lignin), so the physical properties of wood are either improved or worsen. In this study, the effect of thermal treatment on density, equilibrium moisture content (EMC), and color of hornbeam wood was investigated. The color and density (air-dry and oven-dry density) were determined for the control and heat-treated samples, as well as their equilibrium moisture content at relative humidities of 35, 50, 65, 80, and 95%. The data showed that thermal treatment resulted mainly in darkening of the wood and the reduction of its density and EMC. It was found that the treatment temperature had a much more significant impact on color changes than the duration of the treatment. Generally, heat-treated wood color becomes darker than nontreated wood, so it can be used as decorative material. Because the EMC is lower, the heat-treated wood can be used in saunas and pool sides. Also, heat-treated wood can be used in outdoor applications because of lower density.

Keywords Color changes; Density; Equilibrium moisture content; Hornbeam wood; Thermal treatment

INTRODUCTION

Heat treatment of wood has been used to dry wood and modify its properties since ancient times. At present, heat-treated wood can be produced by using different thermal processes yet for the same reasons. Heat treatment of wood has an important effect on its chemical composition and its physical and mechanical properties. In addition to better durability, the features of heat-treated wood include reduced hygroscopicity, improved dimensional stability, and desirable changes in its color. The characteristic properties of heat-treated wood are generally different from those of dry but untreated wood. For example, after thermal treatment, wood is less hygroscopic than kiln-dried wood.[1–4] This feature reveals through reduced swelling and shrinkage, which can be as much as 50% for higher temperatures (>200°C) and longer times. In that context, the sorption and desorption characteristics are also altered. The water uptake by heat-treated wood is slower, and the water release is faster than for kiln-dried wood.[5–7] It is furthermore clear that the equilibrium moisture content is reduced by up to 40% compared with untreated wood.[6,8,9] Dimensional stability and durability, which are strongly associated with the reduction of the hygroscopicity, are improved as a result of the improvement of the product essential properties. However, the loss of strength has always been one of the main drawbacks for the commercial utilization of thermally treated wood.

Heat-treated wood has been found to be brittle compared to kiln-dried wood, especially for treatments over 200°C. This brittleness generally increases with increased treatment temperature and time. The impact strength, modulus of rupture (MOR) bending strength and modulus of elasticity (MOE) can be reduced by up to 50%.[10–14] Hardness and abrasion resistance are also affected and significant reductions have been reported.[11,15–17]

Heat-treated wood is often appreciated for its light- to dark-brown appearance.[8] Therefore, heat-treated wood has been suggested as a substitute for some tropical hardwoods. Both treatment time and temperature can be varied to produce a specific, brownish color. Prolonged treatment time and/or raised temperature usually give the wood a darker color. Furthermore, according to heat treatment temperature and duration, wood generally turns into a lighter and darker material and therefore it has been suggested that the color can be used as an indicator of the degree of conversion[18] and losses in mechanical properties.[14] However, the attained brownish color is not stable when exposed to light.[4,7,19–21]

The colored substances in the wood are eventually degraded and washed out if the wood is exposed outdoors, leaving a bleached and grayish appearance. No cost-effective and easy method to prevent this fading has been described. As opposed to other chemical modification methods,[22] in most thermal treatment processes no reacting chemicals are added during wood treatment. In the thermal treatment of wood, chemical transformations are caused principally by autocatalytic reactions of the cell-wall constituents.

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The cell wall is primarily composed of three polymeric components; i.e., cellulose, hemicellulose, and lignin. It is known that during the thermal treatment of wet wood, carbonic acids, mainly acetic acid, will be formed initially as a result of the cleavage of the acetyl groups of particular hemicelluloses.[23,24]

The aims of this article can be summarized in the following points:

1. To learn more about the color changes that occur in wood after heat treatment and determine how thermal treatment affects the properties of wood.
2. To learn how thermal treatment affects density and equilibrium moisture content (EMC) of hornbeam wood at temperatures of 170, 190, and 210°C and at relative humidities of 35, 50, 65, 80 and 95%.

MATERIALS AND METHODS

The hornbeam (*Carpinus betulus* L.) wood samples used during this study were obtained in Bartin, Turkey. They were dried in air, with initial moisture contents from 11 to 13%. Thermal treatment was performed with the test samples placed in an oven at controlled temperatures of 170, 190, and 210 $\pm$ 1°C. For each of the three temperatures, the samples conditioned at 65% RH and 20°C were heated at atmospheric pressure in the presence of air for three different periods of time; i.e., 4, 8, and 12 h. The density changes caused by heat treatment were determined from mass of a given specimen and its volume calculated from size measurements in tangential, radial, and longitudinal directions.

The changes in density were calculated according to ASTM D 2395-07.[25] Tests to determine moisture content (MC) were carried out on the same specimens that were subjected to density evaluation. Moisture content was determined for specimens that had been conditioned at 35, 50, 65, 80, and 95% relative humidity conditions and temperature of 20°C. Color measurements of all specimens were taken at the surface of the wood specimens before and after heat treatment by a colorimeter (Minolta Chroma-Meter CR-300 colorimeter–UK). The sensor head was 6 mm in diameter. Measurements were made using a D65 illuminant and 10-degree standard observer. Percentage of reflectance, collected at 10-nm intervals over the visible spectrum (from 400 to 700 nm), was converted into the CIELAB color system,[14] where L^* describes the lightness and a^* and b^* describe the chromatic coordinates on the green-red and blue-yellow axes, respectively. From the L^*, a^*, and b^* values, the difference in the lightness (ΔL^*) and chroma coordinates (Δa^* and Δb^*), hue angle (h), saturation (C^*), and total color differences (ΔEab^*) were calculated according to DIN5033.[26]

RESULTS AND DISCUSSION

The effects of thermal treatment at different temperatures and for different durations are shown in Tables 1 and 2 and Figs. 1 through 6. Table 1 shows the effects on density and color and Table 2 shows the effect of heat treatment on color changes of wood, and Fig. 6 shows changes in equilibrium moisture content (EMC). The values in the Tables 1 and 2 and Fig. 6 refer to the differences between the properties of heat-treated specimens compared to control (untreated) specimens. It was found that, after heat treatment, the density of the wood had decreased, the equilibrium moisture content (EMC) of the wood had decreased, and the color of the wood had gotten darker. Decrease in density and EMC was observed for thermal treatment conditions used in the study. The data were evaluated statistically by one-way ANOVA to determine the effect of heat treatment on density, EMC, and color change. Differences between heat-treated specimens and control specimens were statistically significant at the 5% confidence level. According to the obtained results, for all heat-treatment temperatures and time periods durations, the color of wood became darker and all values of significant physical properties of heat-treated wood decreased.

According to the averages, all properties decreased with increasing temperature and time. It is evident that these values were all lower in heat-treated samples than in control samples. It was shown that density (after oven drying to 12% moisture), color change (Table 1), and EMC (Fig. 6) decrease with increasing temperature and heat treatment time under the conditions used. Heat treatment caused some negative results due to thermal degradation of the wood. One of the major problems is the mass loss. The moisture starts to evaporate at lower temperatures during treatment. However, this phenomenon becomes significant above 100°C. At high temperatures, the physical bonds between water and the hydroxyl groups of the wood components are broken due to the heat supplied to wood. A part of this energy is used for breaking bonds and part for evaporating the moisture. Evaporating ratio increases at high temperature due to boiling and so it continues until all the water is evaporated from wood. After the maximum loss rate is achieved, the mass loss slows as water is depleted. The observed acceleration of mass loss is probably caused by the release of different byproducts during the degradation of wood components, such as hemicelluloses.[27] Therefore, density decreases because mass is lost while the volume remains the same (shrinkage occurs due to moisture removal from the cell wall). Also, color of the wood becomes darker due to the thermal degradation of lignin.

According to Figs. 1 and 2, oven-dry and air-dry densities decreased as a result of thermal treatment. But the rate

TABLE 1
The changes in color changes and oven-dry density of heat-treated hornbeam (*Carpinus betulus* L.) wood at different temperatures and durations

Temperature (°C)	Durations	Statistical values	Density (g/cm^3)		Color values		
			Oven-dry	Kiln-dry	L*	a*	b*
Control		x	0.781	0.794	71.99	11.01	28.55
		±s	0.009	0.012	1.03	0.35	0.94
		v%	1.168	1.512	1.44	3.13	3.29
170	4	x	0.774	0.788	64.05	6.75	21.6
		±s	0.012	0.01	1.13	0.71	0.59
		v%	1.587	1.312	1.77	10.52	2.75
	8	x	0.762	0.76	60.09	7.33	25.74
		±s	0.01	0.009	0.05	0.11	0.68
		v%	1.297	1.16	0.08	1.45	2.63
	12	x	0.751	0.756	36.02	10.06	25.64
		±s	0.014	0.011	1.07	0.29	0.69
		v%	1.925	1.436	2.96	2.91	2.7
190	4	x	0.756	0.784	40.17	9.54	21.65
		±s	0.008	0.007	0.09	0.4	0.71
		v%	1.008	0.846	0.21	4.19	3.28
	8	x	0.741	0.765	38.25	8.21	17.1
		±s	0.007	0.01	1.76	0.26	0.22
		v%	0.977	1.246	4.6	3.15	1.27
	12	x	0.731	0.756	32.65	8.05	15.52
		±s	0.006	0.005	0.8	0.13	0.66
		v%	0.79	0.679	2.44	1.58	4.24
210	4	x	0.72	0.739	28.68	5.31	14.88
		±s	0.013	0.007	0.81	0.53	0.19
		v%	1.85	0.981	2.83	10.02	1.27
	8	x	0.693	0.691	26.01	4.9	11.67
		±s	0.011	0.021	0.5	0.51	0.49
		v%	1.607	3.032	1.93	10.47	4.19
	12	x	0.683	0.666	25.75	1.93	8.75
		±s	0.015	0.017	0.71	0.12	0.36
		v%	2.205	2.584	2.76	6.16	4.12

x, average; ±s, standard deviation; V, coefficient of variation.

TABLE 2
The color changes of heat-treated hornbeam (*Carpinus betulus* L.) wood

Temperature (°C)	Durations	Color changes			
		ΔL*	Δa*	Δb*	ΔEab*
170	4	7.94	4.26	6.95	67.93
	8	11.90	3.68	2.80	65.78
	12	35.97	0.95	2.91	45.34
190	4	31.82	1.47	6.90	46.62
	8	33.74	2.80	11.45	42.70
	12	39.34	2.96	13.03	37.04
210	4	43.31	5.70	13.67	32.74
	8	45.98	6.11	16.88	28.93
	12	46.24	9.08	19.90	27.23

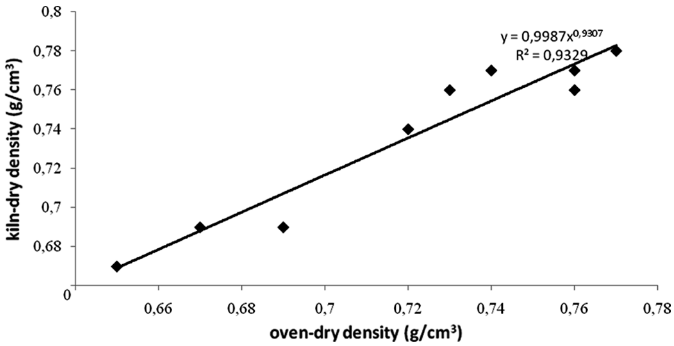

FIG. 1. The relation between oven-dry and air-dry densities of heat-treated wood.

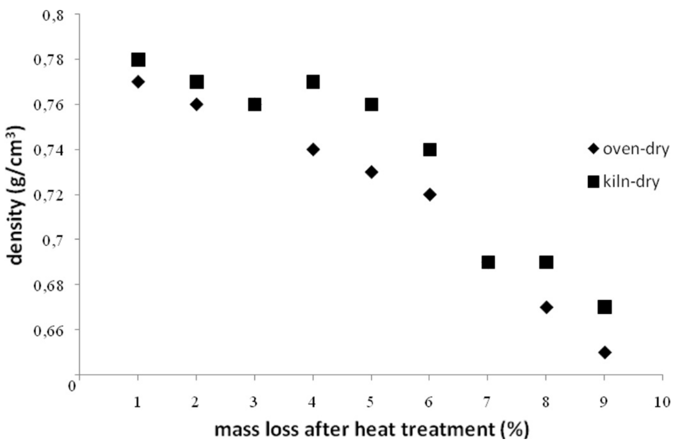

FIG. 2. The effect of mass loss on oven-dry and air-dry densities of heat-treated wood.

of decreasing was not the same for the oven-dry and air-dry samples. At a treatment temperature of 170°C for 4 h, the smallest decreases in oven-dry and air-dry densities were determined to be 1 and 0.75%, respectively. The maximum decreases in oven-dry and air-dry densities were determined to be approximately 14 and 20%, respectively, at the treatment temperature of 210°C for 12 h.

Gunduz et al.[28] found that the oven-dry density and air-dry density values decreased with increasing temperature and time of thermal treatment. In the same study, wood samples heat-treated at 180°C for 10 h exhibited lower air-dry and oven-dry density values than the samples treated under other conditions. Vital and Lucia[29] found that the primary reason for the density reduction was the degradation of hemicelluloses, which are less resistant to heat than cellulose and lignin. Change or loss of hemicelluloses plays the key role in determining the physical properties of wood that has been heated at high temperatures for a certain time.

Figure 3 shows the changes in the L* coordinate of the samples with respect to exposure time for each temperature. At any treatment temperature, L* decreased, indicating that the color had become darker as heat treatment times increased from 4 to 12 h. At 170°C, L* decreased steadily, and the maximum decrease in lightness was approximately 48.21% after 12 h of treatment. Significant darkening of color was observed at 210°C during the first 4 h, and the darkest color occurred (L* reduced by 64.23%) after 12 h of treatment.

Figure 4 shows the changes in a* color of the samples. At all treatment temperatures and times, except for 170°C, the color component a* decreased as time changed from 4 to 12 h. At 170°C, the value of a* increased steadily, but at 190°C the value of a* decreased, and the maximum drop of a* value was approximately 26.88% after 12 h of treatment. At 210°C, a significant darkening was observed

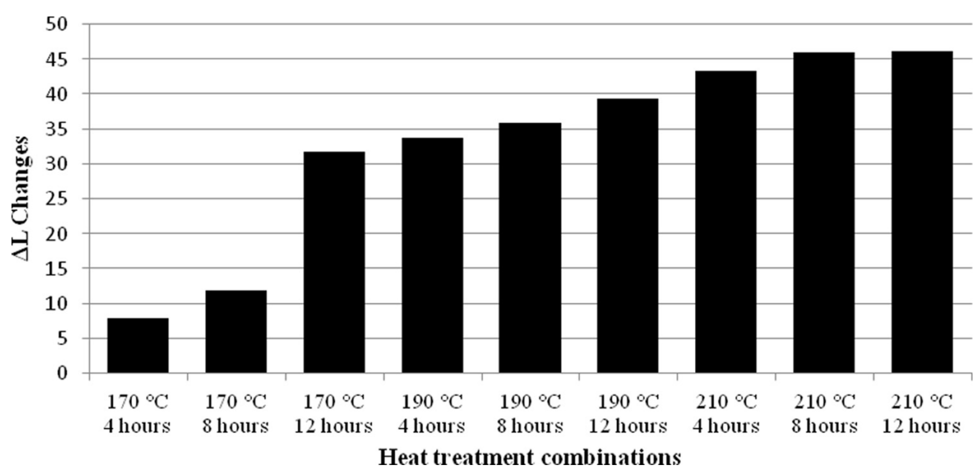

FIG. 3. The effect of heat treatment on L* (lightness) change.

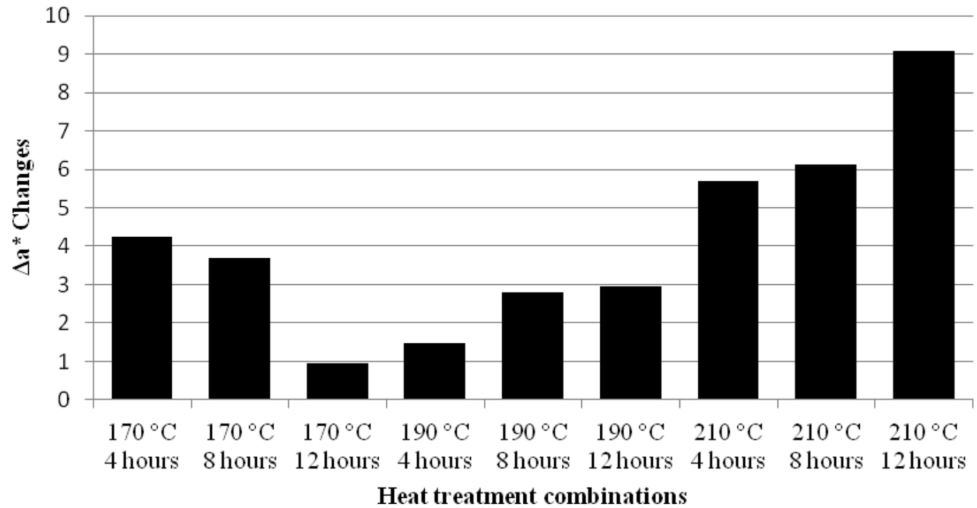

FIG. 4. The effect of heat treatment on a* (red coordinate) change.

during the first 4 h, reaching the lowest value (82.47%) after 12 h of treatment.

Figure 5 shows the changes in the b* color of the samples. At all treatment temperatures, the color component b* decreased as time changed from 4 to 12 h. At 170°C, the value of b* increased steadily, whereas at 190°C, the value of a* decreased, and the maximum loss in the value of a* was approximately 45.53% after 12 h of treatment. At 210°C, the drop of color value b* was observed during the first 4 h, reaching the lowest value (69.35%) after 12 h of treatment. Figure 4 shows the effect of thermal treatmentheat treatment on a* (red coordinate) change for heat-treated wood at various temperatures and times.

Table 2 shows the average color changes of hornbeam (*Carpinus betulus* L.) wood treated at high temperatures (170, 190, and 210°C). According to these results, ΔL* values decreased, as was determined by the increasing values of Δa* and Δb*. The values of Δa* and Δb* for hornbeam wood increased initially at low temperature (170°C) and then decreased at high temperatures (190 and 210°C). As a result, especially the specimens heated at 210°C got darker as compared to control specimens. Generally, it was determined that the ΔEab* value of specimens treated at 210°C indicated higher average color changes than those for specimens treated at 170°C. As shown in Table 2, the ΔEab* values range from 14.3 to 45.52. Bekhta and Niemz[14] obtained similar color change results for hornbeam wood for the same treatment duration and temperature. Schnabel et al.[30] found that the heat treatment at low and medium intensities led to a rise in a* value of beech wood but remained unchanged when applying thermal energy of high intensity. The b* value increased slightly due to low-intensity thermal

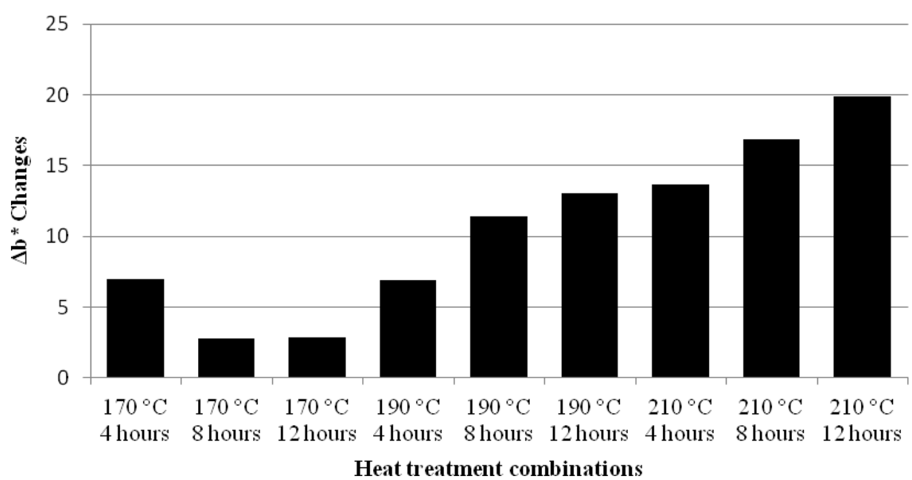

FIG. 5. The effect of heat treatment on b* (yellow coordinate) change.

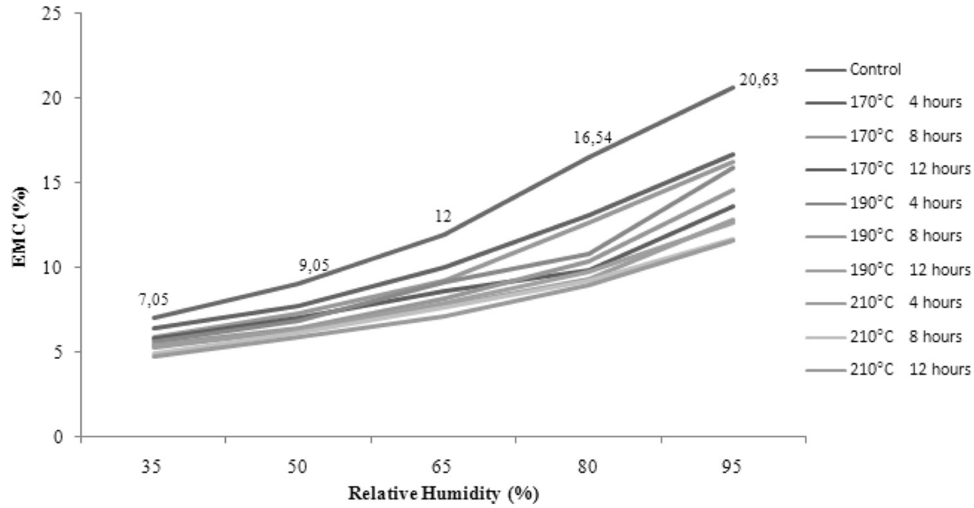

FIG. 6. The changes in equilibrium moisture content at different relative humidity conditions for heat-treated hornbeam (*Carpinus betulus* L.) wood at different temperatures and durations.

treatment. However, even when high temperatures were applied, the b* value decreased.

It was determined that a reduction of the equilibrium moisture content occurred in heat-treated hornbeam wood. When the wood was treated at 170°C for 4 h, the minimum drop in the equilibrium moisture content was lower; i.e., 0.087 at 35% RH; 0.14 at 50% RH; 0.16 at 65% RH; 0.20 at 80% RH; and 0.18 at 95% RH compared to untreated wood, respectively (Fig. 6). The EMC differed for the untreated and the low-intensity treated samples for hornbeam wood. The low-intensity (170°C, 4 and 12 h) treatment of hornbeam samples showed a reduction in EMC from 8.7 to 20%, respectively. Medium-intensity heat treatment at 190°C for 4 and 12 h showed an EMC loss from 22.83 to 37.54% in hornbeam wood, respectively. Hornbeam wood treated at the high intensity level of 210°C for 12 h exhibited the lowest reduction in EMC, from 32.90 to 46%. These results show that, after an intensive thermal treatment of wood, the EMC is decreased as compared with referenced value of the untreated wood. A similar result was reached by Burmester,[31] Giebeler,[32] and Hanger et al.[33] After heat treatment, EMC was determined to decrease due to low water absorption of hornbeam wood, which is generally an explanation of the degradation of wood polymer.

CONCLUSIONS

It was found that the oven-dry and air-dry density, equilibrium moisture content, and color change of the Hornbeam wood decreased with increasing temperature and treatment time for all treatment conditions. The smallest decrease was observed in the treatment at 170°C for 4 h. In this research, all of the significant physical properties of the wood decreased with increasing time and temperature treatments. The most important property, when compared to untreated wood, is that the equilibrium moisture content of the heat-treated wood is reduced.

Due to its good resistance to weather, heat-treated hornbeam wood is suited for outdoor applications such as external cladding, window frames, and garden furniture. As a result of its dimensional stability, heat-treated wood gives better durability for coating. When wood is treated at high temperatures and for long time periods, we recommend that the wood should not be used in structural load-bearing constructions.

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