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The effects of thermal treatment on the mechanical properties of wild Pear (*Pyrus elaeagnifolia* Pall.) wood and changes in physical properties

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ABSTRACT

The aim of the study was to investigate the effects of thermal treatment on the mechanical and physical properties of wild pear wood. The results obtained for thermal treatment at 160 °C for 2 h showed that the modulus of elasticity was increased about 5%, while bending strength and compression strength decreased by 7.42% and 7.55%, respectively. The physical properties of wild pear wood were improved as 2.6%, 5.3%, 8.5% and 0.8% swelling in tangential, radial and longitudinal sections and 1.7%, 1.1% and 0.9% at 50, 65 and 85 Rh% and changes in ΔEab^* was 8.50%, respectively. It was determined that the changes ratio of these properties increased as the temperature and durations were increasing. Therefore, wild pear wood can be used as an alternative for tropical woods in decoration and veneer industry.

1. Introduction

When wood is heated, its chemical and physical properties undergo permanent changes and its structure is reformed. The observed changes in properties are occurred mainly due to the degradation of hemicelluloses. The changes continue as the temperature is increased during heating process. As a result, swelling due to moisture absorption reducing decrease, biological durability improves, color darkens, several extractives flow from the wood, pH decreases, thermal insulation properties improve, and the density of the wood decreases.

The degradation of hemicelluloses changes the hygroscopic behavior of wood. Moisture absorption is reduced, and any water that penetrates into the wood evaporates quickly, since it is not readily adsorbed, and these changes contribute to the enhancement of the dimensional stability and the fungal resistance of the wood. Thermally treated wood is less hygroscopic than kiln-dried wood [1–3].

This can be noted as a reduced swelling, and the reductions can be as much as 50% at higher treatment temperatures (>200 °C) and longer treatment times. In that context, the sorption and desorption characteristics are also changed. The water uptake in thermal-treated wood is slower, and the water release is faster than kiln-dried wood [4–6]. It is furthermore clear that the equilibrium moisture content (EMC) is reduced by up to 40% compared with untreated wood [7,8,6,3].

The properties of thermally-modified wood differ from those of untreated wood. The color of the wood is modified, and the new color is uniform throughout the thickness of wood. Thus, thermal modification can be used to make a low-value wood species have the appearance of a high-value wood species (e.g., cherry, teak, and walnut). Dimensional stability and resistance to fungal degradation are enhanced, but mechanical performance is reduced. With careful selection of applications where the treatment is beneficial, the performance of some under-utilized species can be improved and the value of these species can be enhanced. For use as garden furniture, hardwood flooring, or siding, the potential is almost endless.

Thermal-treated wood is often appreciated for its appearance, which ranges from light brown to dark brown [7]. Therefore, thermal-treated woods have been suggested as substitutes for some tropical hardwoods. Both treatment time and temperature can be varied to produce a specific brownish color. Longer treatment times and/or higher temperatures usually give the wood a darker color. Because color darkens as treatment times and temperatures increase, it has been suggested that color can be used as an indicator of the degree of conversion [9] and an indicator of the extent of the losses in mechanical properties [10]. However, the brownish color that results from thermal treatment is not stable against sunlight exposure [11–13], and the wood becomes more brittle and mechanical strength decreases depending on the level of thermal treatment [10,14,15].

Bekhta and Niemz [10] reported that both bending strength and modulus of elasticity decreased when the treatment temperature was more than 100 °C, and a 50% decrease in bending strength was observed for spruce wood treated at 200 °C. According to

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Schneider [16], beech and pine wood exposed to temperatures of 100, 130, 150, 180, and 200 °C for durations of 6, 24, and 48 h showed decreased compression strength values. After the treatment of pine sapwood and beech wood at 180 °C, it was observed that the compression strength beech wood decreased more than the compression strength of pine sapwood. According to Yıldız et al. [17], when beech wood and Spruce wood were thermal-treated at 130, 150, and 200 °C, the minimum loss in compression strength was observed at 130 °C for 6 h, and the maximum loss (36%) was observed when the woods were treated at 200 °C for 10 h.

Several studies concerning the effects of thermal treatment on the mechanical and physical properties of wild pear (*Pyrus elaeagnifolia* Pall.) wood have been conducted. In this paper, we have evaluated changes that occur, i.e., color, compression strength, bending strength, modulus of elasticity, density, swelling in different directions (tangential, radial and longitudinal), equilibrium moisture content, and color variations, when wild pear wood is thermal-treated.

2. Material and methods

The wild pear (*Pyrus elaeagnifolia* Pall.) samples used during this study were obtained from Beypazari, Turkey. Wild pear lumber was planed in a local mill and clean specimens were obtained. The dimensions of the samples used to determine the physical properties were $20 \times 20 \times 30$ mm. Small clean specimens with the aforementioned dimensions were cut from lumber for use in determining compression strength parallel to grain, and specimens with dimensions of $20 \times 20 \times 360$ mm were obtained for use in determining modulus of elasticity and bending strength. The specimens were sawn with the annual rings at a 40° angle to the surface so that the deformations would be smaller. According to ISO 554 [18], they were dried in air until their moisture contents were in the range of 11% to 13% before the thermal treatment. The test samples were subjected to thermal treatment in a fully-controlled oven with ±1 °C sensitivity at three temperatures (160, 180, and 200 °C) and for three time periods (3, 5, and 7 h) at atmospheric pressure.

Tests of density, equilibrium moisture content, swelling, and color change were conducted on the same samples. Swelling measurements on the samples were conducted to 0.01 mm accuracy at three different marked positions before and after immersion in water for 48 h. The swelling values of the samples were determined using ISO 4859 [19]. To determine the densities (moisture content = 12%) of the samples, they were weighed and their volumes were measured. The densities of the samples were calculated using ISO 3131 [20].

The equilibrium moisture contents (EMC) of the sample, expressed as percentages, were determined at 20 °C and at relative humidities of 50%, 65%, and 85%. The specimens were conditioned until their weights reached equilibrium; then they were weighed, and their EMCs were calculated using ISO 3130 [21].

Color measurements of all specimens were taken on the surface of the wood specimens before and after the thermal treatment process by a Minolta Chroma-Meter CR-300 colorimeter. The sensor head was 6 mm in diameter. Measurements were made using a D65 illuminant and a 10° 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, 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 differences in the lightness (ΔL^*) and chroma coordinates (Δa^* and Δb^*) were calculated according to DIN 5033 [22].

Tests for compression strength perpendicular to grain, modulus of elasticity in bending, and bending strength were conducted in accordance with ISO 3345 [23], ISO 3349 [24], and ISO 3133 [25], respectively. In this study, variance analysis was applied in the analysis of the results. All statistical calculations were based on the 95% confidence level. ANOVA and Tukey's Multiple Range Tests showed that all differences were significant.

3. Results and discussion

The wood specimens that were treated at temperatures of 160 and 180 °C for durations of 2, 4, and 6 h were observed to have improved physical properties and decreased mechanical properties, such as compression strength parallel to grain, bending strength, and modulus of elasticity in bending. The samples also exhibited changes in color properties depending upon treatment temperatures and durations. The results showed that treatment condition of 180 °C for 6 h resulted in the greatest decrease in mechanical properties and the most severe changes in physical properties.

The changes in mechanical and physical properties can be explained by the rate of thermal degradation and losses of substance as a result of the treatment process. This is mainly due to depolymerization reactions of wood polymer [26]. The primary reason for the strength loss is the degradation of hemicelluloses, which are less resistant to heat than cellulose and lignin. It is well known that changes in the hemicelluloses play key roles in the strength properties of wood heated at high temperatures [27]. Table 1 presents statistical data related to the changes in physical properties, such as density, swelling, equilibrium moisture content (EMC), and color changes, as well as mechanical properties, such as compression strength (CS), bending strength (BS), and bending modulus of elasticity (MOE) for wild pear wood after the thermal treatment process.

According to Table 1, the density of wild pear wood decreased with increasing treatment temperatures and times. Heating of wood results in a reduction in mass and a decrease in volume, the extent of which is dependent upon the treatment method, temperature, and time of exposure. It was found that density loss decreased due to this phenomenon. The density decreases were approximately 2% (0.73 g/cm^3), 2.5% (0.73 g/cm^3), and 4% (0.72 g/cm^3) after thermal treatment of wild pear wood at 160 °C for 2, 4, and 6 h. These decreases in density were due to evaporation during heating at 160 °C. The density decreases at 180 °C for 2, 4, and 6 h were 2.5% (0.73 g/cm^3), 4.5% (0.72 g/cm^3), and 5% (0.72 g/cm^3). The highest and lowest decreases in density were determined at 180 °C for 6 h and at 160 °C for 2 h, respectively. The results in Table 1 show that density losses increased during thermal treatment at temperatures of 160 °C and 180 °C. However, it was concluded that the small density decreases that occurred during the thermal treatment process were insignificant. Also, the study showed that temperature was a more important factor than duration in determining density loss. The density of thermal-treated wild pear wood was lower than that of the untreated wood. This phenomenon is mainly due to the greater effect of temperature on material loss as compared to the duration of the thermal treatment.

It was determined that thermal-treated wood absorbed less moisture than the control specimens. When wood was treated at 160 °C and 180 °C for 2, 4, and 6 h was compared to untreated wood, the minimum loss in the EMC was lower by about 2% at 50% RH, 1% at 65% RH, and 0.8% at 85% RH, respectively. The maximum loss in the EMC for thermal-treated wood compared to untreated wood was lower by 6% at 50% RH, 6.5% at 65% RH, and 5% at 85% RH, respectively. The EMC differs among the untreated and the low-intensity (160 °C for 2, 4, and 6 h), strong-intensity (180 °C for 2, 4, and 6 h) treated samples for wild pear wood. The

Table 1
Changes in mechanical properties, such as compression strength (CS), bending strength (BS), and modulus of elasticity (MOE), and physical properties, such as density, swelling, equilibrium moisture content (EMC), and color changes for wild pear wood after heat treatment.

Temp. (°C)	Durations (h)	Statistical values	Physical properties											Mechanic properties		
			Density (g/cm^3)	EMC (%)			Swelling (%)			Color changes				CS (N/mm^2)	BS (N/mm^2)	MOE (N/mm^2)
				%50 Rh	%65 Rh	%85 Rh*	Tangential	Radial	Longitudinal	ΔL^*	Δa^*	Δb^*	ΔEab^*			
		x	**0.75A**	**9.84A**	**12.79A**	**15.65A**	**5.59A**	**3.85A**	**0.36A**	**75.85A**	**6.56A**	**19.41AB**	**78.57A**	**51.04A**	**83.76A**	**6727.02A**
Control	–	±*s*	*0.03*	*0.74*	*1.03*	*0.74*	*0.32*	*0.51*	*0.05*	*2.99*	*1.06*	*2.6*	*4.12*	*3.53*	*7.82*	*458.55*
		v%	*3.96*	*7.52*	*8.09*	*4.73*	*5.75*	*13.16*	*13.89*	*3.94*	*16.18*	*13.41*	*5.24*	*6.92*	*9.33*	*6.82*
		x	**0.73B**	**9.67AB**	**12.65A**	**15.51B**	**5.29AB**	**3.52AB**	**0.36A**	**68.01B**	**9.74B**	**21.17B**	**71.89B**	**47.25B**	**77.43BC**	**7060.05AB**
	2	±*s*	*0.03*	*0.69*	*0.88*	*0.6*	*0.23*	*0.4*	*0.05*	*3.16*	*0.6*	*0.75*	*0.77*	*1.63*	*6.39*	*582.44*
		v%	*0.03*	*7.16*	*6.97*	*3.86*	*4.43*	*11.36*	*13.6*	*4.64*	*6.12*	*3.55*	*1.07*	*3.45*	*8.25*	*8.25*
		x	**0.73B**	**9.47AB**	**12.52AB**	**15.32B**	**5.27AB**	**3.45AB**	**0.35A**	**58.92C**	**10.04C**	**20.43B**	**63.16C**	**44.72CDE**	**72.56**	**6869.26A**
160	4	±*s*	*0.03*	*0.6*	*0.43*	*0.77*	*0.42*	*0.57*	*0.05*	*2.53*	*0.81*	*3.03*	*0.9*	*1.98*	*4.5*	*431.42*
		v%	*0.03*	*6.32*	*3.46*	*5*	*8.03*	*16.41*	*15.54*	*4.29*	*8.02*	*14.81*	*1.42*	*4.43*	*6.2*	*6.28*
		x	**0.72B**	**9.51AB**	**12.12AB**	**15.06C**	**5.21AB**	**3.25AB**	**0.30AB**	**55.84D**	**9.59C**	**19.42AB**	**59.90D**	**44.04DE**	**65.83CDE**	**6144.14BC**
	6	±*s*	*0.03*	*0.74*	*1.03*	*0.56*	*0.6*	*0.36*	*0.05*	*1.68*	*0.69*	*1.1*	*0.83*	*1.77*	*2.01*	*285.49*
		v%	*0.03*	*7.81*	*8.53*	*3.75*	*11.44*	*11.12*	*15.28*	*3*	*7.17*	*5.69*	*1.38*	*4.03*	*3.05*	*4.65*
		x	**0.73B**	**9.67AB**	**12.50ABC**	**15.34B**	**5.15AB**	**3.77A**	**0.33A**	**58.01CD**	**10.03B**	**20.45B**	**62.32C**	**45.34BCD**	**75.72BCD**	**6645.96AB**
	2	±*s*	*0.03*	*0.77*	*0.47*	*0.43*	*0.68*	*0.24*	*0.06*	*1.86*	*0.54*	*1.67*	*0.74*	*2.52*	*5.46*	*1627.83*
		v%	*0.03*	*7.92*	*3.78*	*2.82*	*13.26*	*6.42*	*18.63*	*3.21*	*5.39*	*8.19*	*1.18*	*5.55*	*7.21*	*24.49*
		x	**0.72B**	**9.44AB**	**12.27BC**	**15.04D**	**4.81B**	**3.63AB**	**0.31AB**	**47.73E**	**8.53C**	**17.76BC**	**51.64CD**	**42.62CDE**	**71.27BCD**	**6545.86BC**
180	4	±*s*	*0.03*	*0.78*	*0.44*	*0.47*	*0.55*	*0.59*	*0.05*	*2.3*	*0.69*	*1.18*	*0.83*	*0.78*	*3.82*	*701.6*
		v%	*0.03*	*8.25*	*3.6*	*3.15*	*11.52*	*16.18*	*16.31*	*4.82*	*8.03*	*6.65*	*1.6*	*1.84*	*5.37*	*10.72*
		x	**0.72B**	**9.25C**	**11.94C**	**14.86E**	**4.74B**	**3.54AB**	**0.30AB**	**43.07F**	**8.40C**	**17.14C**	**47.11E**	**41.48E**	**61.92**	**5974.97C**
	6	±*s*	*0.03*	*0.56*	*0.72*	*0.72*	*0.49*	*0.36*	*0.04*	*2.32*	*0.73*	*1.27*	*0.86*	*1.19*	*5.13*	*450.76*
		v%	*0.03*	*6.1*	*6.05*	*4.86*	*10.33*	*10.09*	*13.54*	*5.39*	*8.73*	*7.38*	*1.82*	*2.88*	*8.28*	*7.54*

x: Average, ±*s*: Standard deviation, *v*: Coefficient of variation, *Homogeneity groups*: Same letters in each column indicate that there is no statistical difference between the samples according to the Duncan's multiply range test at $p < 0.05$. Comparisons were done between the each control and test. Thirty replicates were used in each test. All data in Variance and one-way ANOVA tests were done at a confidence level of $p < 0.05$ (95%). Rh*, relative humidity.

low-intensity treated wild pear samples, at a relative humidity of 65%, showed reductions in EMC from 0.8% to 2%, respectively. Strong-intensity thermal-treated wood, at a relative humidity of 65%, showed reductions in EMC from 5% to 6.5%, respectively. These results showed that, after thermal treatment of wood, the EMC decreased as compared to the control specimens.

According to the average reductions at 160 °C and 180 °C, the swelling reductions in tangential, radial, and longitudinal sections were approximately 9%, 7%, and 12% and 12.5%, 11%, and 14%, respectively. In general, the swelling reductions in the tangential direction were found to be greater than the reductions in the radial and longitudinal directions. According to Table 1, the lowest decrease of swelling in the tangential, radial, and cross-sectional directions, as compared to control specimens, was obtained for treatment conditions of 160 °C for 2 h. The highest decrease ratio of swelling was found at 180 °C for 6 h. Swelling reductions of the thermal-treated wood were lower compared to untreated wood, indicating that swelling in different sections was decreased during thermal treatment process.

According to the results obtained, the samples treated at 180 °C for 6 h were found to be darker than the other samples. The color values for the different temperatures indicated differences in the effect of temperature on color changes. In this study, L^* values in color change tests decreased after thermal treatment, and a^* and b^* values generally increased, although they did decrease for treatment conditions of 180 °C for 4 and 6 h. Also, the highest and lowest decreases in L^* were found for the treatments at 160 °C for 2 h and 180 °C for 6 h. After the thermal treatment process, it was determined that ΔEab^* values ranged between 72 and 48.

Gunduz et al. [5] found that the largest decreases of density were 0.519 and 0.509 at 180 °C for 6 h and 200 °C for 6 h. The minimum and maximum decrease values for density were 0.928% at 160 °C for 2 h and 7.66% at 200 °C for 6 h, respectively. The decreases in density are mainly related to mass loss, so increases in mass loss from thermal-treated wood simultaneously affects both the density and the mechanical properties of the wood [6,5].

A similar result was reached by Burmester [28], Giebeler [29], and Hanger [30]. After thermal treatment, EMC was determined to decrease due to low water absorption of hornbeam wood. Burmester [28] stated that the decrease in polyose (hemicellulose) during thermal treatment was the reason for the results that showed that the treatment level could be set to create a product that would have a desired EMC for a specified, end-use ambient climate (temperature and relative humidity).

Thermal treatment significantly reduces tangential and radial swelling to very low values. Desired changes begin to appear at about 150 °C, and the changes continue as the temperature is increased in stages [31]. In another study [4], the technique used suggested that increases in temperature and treatment times resulted in changes in dimensional stability from 55% to 90%.

According to some previous studies, the cause of color changes after thermal treatment is the hydrolysis of hemicelluloses. According to one study, the yellowish color that occurs can be explained by the disintegration of hemicelluloses and the increase in low-molecular-weight sugars produced by thermal degradation. So, it was concluded that the extent of thermal degradation is directly related to the extent of the darkening of the color properties [13].

The effect of thermal treatment on compression strength (CS) of wild pear wood is shown in Fig. 1. According to Fig. 1, as treatment time increases from 2 h to 6 h at different temperatures, CS decreases during the heat-treatment process. After heat treatment, the CS was determined to be 47.25 N/mm^2 for 2 h, 44.72 N/mm^2 for 4 h, and 44.04 N/mm^2 for 6 h at 160 °C. At 180 °C, CS was determined to be 45.34 N/mm^2 for 2 h, 42.62 N/mm^2 for 4 h, and 41.48 N/mm^2 for 6 h, as compared to the control specimens. The

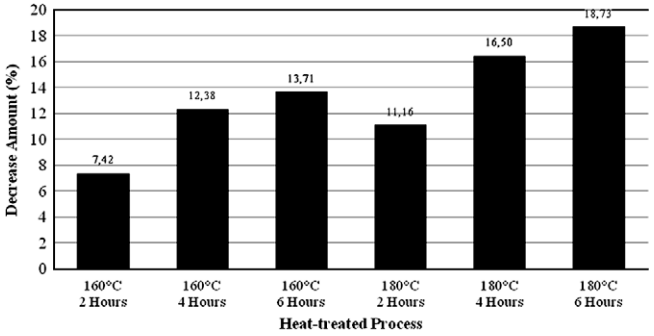

Fig. 1. Changes in compression strength of Wild pear wood.

percentages of CS losses for 2, 4, and 6 h were found to be 7.42%, 12.38%, and 13.71% at 160 °C and 11.16%, 16.49%, and 18.73% at 180 °C.

According to Fig. 2, the lowest decrease in BS, 7.5%, as compared to control specimens, was determined to occur at 160 °C for 2 h. The percentage decreases in BS at 160 °C for 2, 4, and 6 h were 7.50%, 13.37% and 21.40%, respectively. According to Fig. 3, it was determined that MOEs at 160 °C for 2, 4, and 6 h were determined to be 7060.05 N/mm^2, 6869.26 N/mm^2, and 6144.14 N/mm^2, respectively. At 180 °C for 2, 4, and 6 h, MOEs were determined to be 6645.96 N/mm^2, 6545.86 N/mm^2, and 5974.97 N/mm^2. The highest decrease in BS was found to be 26.02% at 180 °C for 6 h as compared to control specimens. While the BS had a minimum decrease at 160 °C for two treatment times, the MOE in this treatment period was shown to have a maximum increase. The increasing percentages were determined to be 4.9% at 160 °C for 2 h. The modulus of elasticity values for the other treatment times and temperatures decreased. According to the results obtained in the heat treatment of wild pear wood at 160 and 180 °C for various treatment times, it was found that mechanical properties were affected in the range of 2.5–27%.

Korkut [32] determined that, for the heat treatment of Scots pine (*Pinus sylvestris* L.) at 120, 150, and 180 °C for 2, 6, and 10 h, the maximum CS losses were observed to be 25.4% at 180 °C and 10 h of treatment. In a study of the effect of heat treatment with pine sapwood heated at 110, 130, 150, and 180 °C, it was found that compression strength decreased by 5% [33].

Unsal and Ayrilmis [34] also found that the maximum decrease in compression strength parallel to grain in Turkish river red gum (*E. camaldulensis* Dehn.) wood samples was 19.0% at 180 °C and 10 h.

Yildiz [4] showed that compression strength of wood decreases when the wood is heated and increases when the wood is cooled. This is exactly the effect achieved with the treatment when applied for a long time. The results indicate that temperature might have greater influence on strength properties than treatment duration.

Yildiz [4] observed that the lowest bending strengths for beech and spruce occurred when the wood samples were treated at

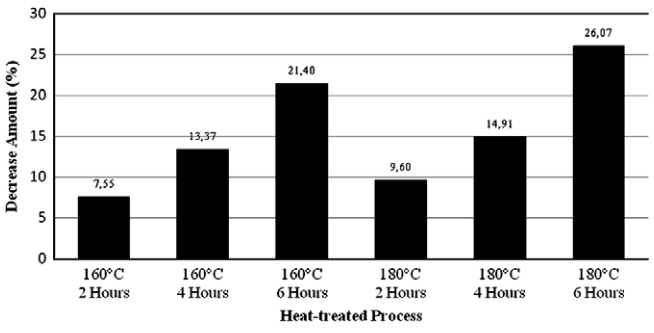

Fig. 2. Changes in bending strength of Wild pear wood.

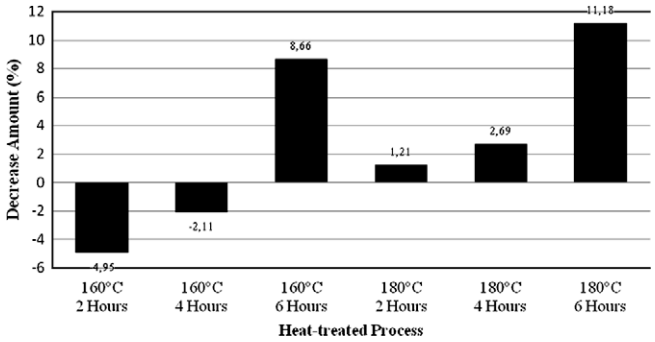

Fig. 3. Changes in modulus of elasticity of Wild pear wood.

200 °C for both 6 and 10 h. The decreases were 63.9% and 63.6% for beech and 63.8% and 72.7% for spruce for 6 and 10 h treatment times at 200 °C. The highest decrease in modulus of elasticity for spruce was 41.5% at 200 °C for 6 h. On the other hand, a slight increase (8, 4%) in modulus of elasticity was observed at 130 °C for samples treated for 10 h. For beech, heat treatment at 200 °C for 10 h resulted in a 39% increase in the modulus of elasticity. In another study, the highest values of bending strength were reached when the treatment temperature was 100 °C.

Bekhta and Niemz [10] found that the bending strength of spruce wood decreased in the range of 44–50% as the treatment temperature was raised from 100 to 200 °C, whereas temperature had no effect on the modulus of elasticity. The modulus of elasticity was lower for the wood specimens dried at room temperature (20 °C) at 95% RH and higher at 35% and 65% RH than for the specimens heated at 100–200 °C. When the wood was dried at room temperature, the bending strength was 5% lower than it was for wood specimens heated at 100 °C and 150 °C, respectively, and it was about 33% higher than it was in wood specimens heated at 200 °C.

4. Conclusions

Wild pear wood has a high density, is dried hardly, and has a desirable color for decorative material. The color of Wild pear wood can be improved with the thermal treatment process. The physical properties of heat-treated Wild pear wood were improved from 2% to 17%. At the same time, the mechanical properties of the heat-treated wood decreased by 8–26%. After the thermal treatment process, physical properties were improved, and the losses of mechanical properties were not high percentages. Therefore, wild pear wood can be used as an alternative for tropical woods in decorative materials, the veneer industry. Finally, the improvement in the physical properties of the wood and the small decreases in its mechanical properties indicate that the material properties of the heat-treated wood have been improved by heat treatment at temperatures of 180 °C and below.

References

[1] Tjeerdsma BF, Boonstra M, Militz H. Thermal modification of non-durable wood species 2. Improved wood properties of thermal-treated wood. International research group on wood production, IRG/WP 98-40124. Maastricht, The Low Countries; 1998.
[2] Obataya E, Tanaka F, Norimoto M, Tomita B. Hygroscopicity of heat-treated wood 1. Effects of after-treatments on the hygroscopicity of heat-treated wood. J Wood Sci 2000;46:77–87.
[3] Gunduz G, Niemz P, Aydemir D. Changes in specific gravity and equilibrium moisture content in heat-treated fir (*Abies nordmanniana* subsp. *bornmulleriana* Mattf.) wood. Dry Technol 2008;26(9):1135–9.
[4] Yildiz S. Physical, mechanical, technological and chemical properties of beech and spruce wood treated by heating. PhD dissertation. Karadeniz Technical University, Trabzon, Turkey; 2002. p. 200.
[5] Gunduz G, Korkut S, Sevim Korkut D. The effects of heat treatment on physical and technological properties and surface roughness of Camiyanı Black Pine (*Pinus nigra* Arn. subsp. *pallasiana* var. *pallasiana*) wood. Biores Technol 2007;99:2275–80.
[6] Aydemir D. The effect of heat treatment on some physical, mechanic and technological properties of Uludag Fir (*Abies bornmülleriana* Mattf.) and Hornbeam (*Carpinus betulus* L.) Wood. Master thesis. Zonguldak Karaelmas University, Zonguldak, Turkey; 2003. p. 169.
[7] Viitanen HA, Jamsa S, Paajanen LM, Nurmi AJ, Viitaniemi P. The effect of heat treatment on the properties of spruce. International research group on wood production, IRG/WP 94-40032. Nusa Dua, Bali, Indonesia; 1994.
[8] Viitaniemi P, Lamsa S. Modification of wood with heat treatment. VTT Build Technol 1996:1–7.
[9] Bourgois J, Janin G, Guyonnet R. Measuring color: a method of studying and optimizing the chemical transformations of thermally-treated wood. Holzforschung 1991;45(5):377–82.
[10] Bekhta P, Niemz P. Effect of high temperature on the change in color, dimensional stability and mechanical properties of spruce wood. Holzforschung 2003;57(5):539–46.
[11] Jämsä SP, Ahola P, Viitaniemi P. Long-term natural weathering of coated ThermoWood. Pigm Resin Technol 2000;29:68–74.
[12] Ayadi N, Lejeune F, Charrier F, Charrier B, Merlin A. Color stability of heat-treated wood during artificial weathering. Holz als Roh-und Werkstoff 2003;61(3):221–6.
[13] Mitsui K, Murata A, Kohora M, Tsuchikawa S. Color modification of wood by light irradiation and heat treatment. In: Van Acker J, Hill CAS, editors. Proceedings of the first European conference on wood modification, Ghent, Belgium; 2003. p. 43–52.
[14] Sailer M, Rapp AO, Leithoff H. Improved resistance of Scots pine and spruce by application of an oil–heat treatment. International research group on wood production, IRG/WP 00-40162. Kona, Hawaii, USA; 2000.
[15] Viitaniemi P. Decay-resistant wood created in a heating process. Indus Horiz 1997;23:77–85.
[16] Schneider A. Investigation on the convection drying of lumber at extremely high temperatures. Holz als Roh-und Werkstoff 1973;31:198–206.
[17] Yıldız S, Gezer EG, Yıldız ÜC. Mechanical and chemical behavior of spruce wood modified by heat. Build Environ 2006;41(12):1762–6.
[18] ISO 554. Standard atmospheres for conditioning and/or testing, specifications, Geneva, Switzerland; 1976.
[19] ISO 4859. Wood – determination of radial and tangential swelling, Geneva, Switzerland; 1982.
[20] ISO 3131. Wood – determination of density for physical and mechanical tests, Geneva, Switzerland; 1975.
[21] ISO 3130. Wood – determination of moisture content for physical and mechanical tests, Geneva, Switzerland; 1975.
[22] DIN 5033. Colorimeters: colorimetric measures, Berlin, Germany; 1992.
[23] ISO 3345. Wood – determination of ultimate compression stress parallel to grain, Geneva, Switzerland; 1975.
[24] ISO 3349. Wood – determination of modulus of elasticity in static bending, Geneva, Switzerland; 1975.
[25] ISO 3133. Wood – determination of ultimate strength in static bending, Geneva, Switzerland; 1975.
[26] Kotilainen R. Chemical changes in wood during heating at 150–260 °C. PhD thesis. Jyaskyla University, Finland; 2000. p. 80.
[27] Hillis WE. High temperature and chemical effects on wood stability. Wood Sci Technol 1996;18:281–93.
[28] Burmester A. The dimensional stabilization of wood. Holz als Roh-und Werkstoff 1995;2(2):112–9.
[29] Giebeler E. Dimensional stabilization of wood by moisture-heat-pressure treatment. Holz als Roh-und Werkstoff 1983;41:87–94.
[30] Hanger J. Physical properties of domestic species after thermal treatment. Holzforschung 2002;6:111–3.
[31] Jamsa S, Ahola P, Viitaniemi P. Performance of coated heat-treated wood. Surf Coat Int 1999;82:297–300.
[32] Korkut S, Akgul M, Dundar T. The effects of heat treatment on some technological properties in Scots Pine (*Pinus sylvestris* L.) wood. Biores Technol 2008;99(6):1861–8.
[33] Schneider A. Investigations on the influence of heat treatment in the temperature range 100–200°C on modulus of elasticity. Holz als Roh-und Werkstoffe 1971;29(11):431–40.
[34] Unsal O, Ayrilmis N. Variations in compression strength and surface roughness of heat-treated Turkish river red gum (*Eucalyptus camaldulensis* Dehn.) wood. J Wood Sci 2005;51:405–9.