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Full Length Research Paper

The effects of heat treatment on physical and technological properties and surface roughness of European Hophornbeam (*Ostrya carpinifolia* Scop.) wood

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Heat treatment of wood is an effective method to improve the dimensional stability and durability against biodegradation. In this study, the effects of heat treatment on physical properties and surface roughness of European Hophornbeam (*Ostrya carpinifolia* Scop.) wood were examined. Samples obtained from Alapli-Zonguldak Forest Enterprises, Turkey, were subjected to heat treatment at varying temperatures and for varying durations. The physical properties of heat-treated and control samples were tested, and oven-dry density, air-dry density, and swelling properties were determined. The mechanical properties of heat-treated and control samples were tested, and compression strength parallel to grain, bending strength, modulus of elasticity in bending, Janka-hardness (cross-section, parallel and perpendicular to grain), impact bending strength, and tensile strength perpendicular to grain were determined. A stylus method was employed to evaluate the surface characteristics of the samples. Roughness measurements by the stylus method were made in the direction perpendicular to the fiber. Four main roughness parameters, mean arithmetic deviation of profile (Ra), mean peak-to-valley height (Rz), root mean square roughness (Rq), and maximum roughness (Ry) obtained from the surface of wood were used to evaluate the effect of heat treatment on the surface characteristics of the specimens. Significant difference was determined (p = 0.05) between physical and technological properties, and surface roughness parameters (Ra, Rz, Ry, Rq) for three temperatures and three durations of heat treatment. Based on the findings in this study, the results showed that oven-dry density, air-dry density, swelling, compression strength parallel to grain, bending strength, modulus of elasticity in bending, Janka-hardness (cross-section, parallel and perpendicular to grain), impact bending strength, tensile strength perpendicular to grain and surface roughness values decreased with increasing treatment temperature and treatment times. Increase in temperature and duration further diminished technological strength values of the wood specimens. European Hophornbeam wood could be utilized by using proper heat treatment techniques without any losses in strength values in areas where working, stability, and surface smoothness, such as in window frames, are important factors.

Key words: Heat treatment, mechanical properties, surface roughness, European Hophornbeam.

INTRODUCTION

European Hophornbeam (*Ostrya carpinifolia* Scop.), having superior technological properties and having high usage potential, is an important species in lumber industry. European Hophornbeam shows an expansive distribution from South France to Bulgaria, West Syria, Anatolia and Transcaucasia. In Turkey, *O. carpinifolia* is found primarily in north and south Anatolia as small groups in angiosperm mixed forests (Davis, 1982; Ansin et al., 1998; Ansin and Ozkan, 2001; Yaltirik and Efe,

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2000). It spreads over 1957.4 ha, which consists only 0.01% of the total forest area in Turkey (Konukcu, 1998; Anonymous, 2001). The only pure stand (approximately 2 ha) of this species in Turkey is found along a valley between 450 and 660 m altitudes in Cide-Sehdagi (Gercek et al., 1998; Dogu et al., 2000).

One of the endemic wood species in Turkey, European Hophornbeam having 15 - 20 m length, has an important industrial usage. It is reported that Ostrya spp. have been used for different purposes such as furniture, axles, handles, levers, mallets, splitting wedges, canes, carpentry, wooden wares, novelties, fuel wood and charcoal (Alden, 1995; Bozkurt and Erdin, 1997, 1998).

Heat treatment of wood at relatively high temperatures ranging from 150 to 260°C is an effective method to improve dimensional stability and durability (Seborg et al., 1953; Kollmann and Schneider, 1963; Stamm, 1964; Kollmann and Fengel, 1965; Noack, 1969; Burmester, 1973 and 1975; Giebeler, 1983; Hillis, 1984; Bourgois and Guyonnet, 1988). Thermally treated wood has been investigated since the middle of the last century and is nowadays produced industrially in many European countries. In the last decade several research groups have been developing heat treatment methods which are suitable for industrial applications (Viitaniemi and Jamsa, 1996; Weiland and Guyonnet, 1997; Boonstra et al, 1998). Some of the products developed by thermal treatment include thermowood (Stellac) in Finland (Viitaniemi et al., 1994), torrefaction (perdure) in France (Weiland and Guyonnet, 1997) and PLATO-wood in The Netherlands (Militz, 2002).

Temperatures over 150°C alter the physical and chemical properties of wood permanently. Heat treatment significantly reduces the tangential and radial swelling. The wood's swelling and shrinkage is very low. Desired changes start to appear already at about 150°C, and the changes continue as the temperature is increased in stages (Anonymous, 2003). Wood treated at high temperature has less hygroscopicity than natural wood. Heating wood permanently changes several of its chemical and physical properties. The change in properties is mainly caused by thermic degrading of hemicelluloses. Theoretically, the available OH groups in hemicellulose have the most significant effect on the physical properties of wood. Heat treatment slows water uptake and wood cell wall absorbs less water because of the decrease of the amount of wood's hydroxyl groups. As a consequence of the reduced number of hydroxyl groups the swelling and shrinking are lower. In addition to beter durability the advantages of heat-treated wood are reduced hygroscopicity and improved dimensional stability (Inoue et al., 1993).

In addition, heat treatment resulted in varying amounts of weight loss, depending on the treatment temperature and time. In a study on Spruce (*Picea abies*) wood, heat treatment for 24 h resulted in a weight loss of 0.8 and 15.5% at 120 and 200°C, respectively (Fengel, 1966). Weight loss of beech (*Fagus sylvatica*) wood, treated at increasing temperatures, was 8.1 and 9.8% at 150 and 200°C respectively (Fengel and Wegener, 1989). Zaman et al. (2000) reported mass losses of 6.4, 7.1 and 10.2% for *Betula pendula* treated at 205°C for 4, 6 and 8 h.

Along with the improvement in durability, some unwanted effects arise, such as reduction of wood strength (Noack 1969; Rusche 1973; Kubojima et al., 2000) and reduction of hardness (Sandermann and Augustin, 1963).

The extent of the change in timber properties during heat treatment depends on the maximum temperature and the maximum length of the actual heat, treatment period, the temperature gradient, the maximum length of the entire heat treatment, the use and amount of water vapour, the kiln drying process before the actual heat treatment and the wood species and its characteristic properties (Anonymous, 2003).

Improved durability is often accompanied by reduction in mechanical strength of wood from the industrial processes used today. Heat-treated wood with considerable durability is obtained at temperatures around 250°C, while mechanical strength drops markedly for treatments at temperatures over 200°C (Syrjänen et al., 2000). Another feature of heat-treated wood is the change in colour to red-brown. Such material has been suggested as an alternative to the use of dark-coloured wood products from tropical species (Bourgois et al., 1991; Bekhta and Niemz, 2003).

The improved characteristics of heat-treated timber of European Hophornbeam wood will offer the timber product industry many potential interesting opportunities. Heat-treated wood is an ecofriendly alternative to impregnated wood materials, and heat-treated wood can be used for garden, kitchen and sauna furniture, cladding on wooden buildings, bathroom cabinets, floor material, musical instruments, ceilings, iner and outer bricks, doors and window joinery, and a variety of other outdoor and indoor wood applications (Syrjanen and Oy, 2001).

Research on the effects of heat treatment on the physical and mechanical properties and surface roughness of Turkish native trees is rather limited. The aim of the study was to fulfill the gap in the literature and to facilitate optimal utilization fields of this species. European Hophornbeam (*Ostrya carpinifolia* Scop.) is one of the most common wood species naturally grown and intensively used in the forest product industry in Turkey. Improving the characteristics of European Hophornbeam through heat treatment would offer the timber product industry many interesting opportunities.

MATERIALS AND METHODS

Five trees with a diameter at breast height diameter (DBH. 1.3 m above ground) of 34 - 42 cm were obtained from Alapli-Zonguldak Forest Enterprises (TS 4176). The area from which the trees were taken was at an average altitude of 650 m and had a slope of 60%. Lumber from the logs was prepared by AKE Sawmill Ltd. European Hophornbeam lumber was finished by a fixed-knife planer with a feed speed of 1 m/s. The bias angle of the knife was 45° for the lumber. If the wood pieces are sawn so that the annual rings are at least in 45° angle to the surface the deformations will be smaller, the hardness of the surface will be stronger and the ‘‘general looks’’ after heat treatment is better.

Boards with 8 cm width were cut from logs according to TS 2470 and TS 53 (same ISO 3129). Sawdust removed from surfaces and boards were stored uncontrolled condition in an unheated room for air drying.

Following air-drying process, small and clear specimens were cut from the boards according to Turkish standards (TS) to determine air-dry and oven dry densities (D_{m12}, D_{m0}) (TS 2472 same ISO 3131), swelling [(tangential, radial, longitudinal) (α(t, r, l))] (TS 4084 same ISO 4859), compression strength parallel to grain ($\sigma_{c//}$) (TS 2595 same ISO 3787), bending strength (MOR) (TS 2474 same ISO 3133), modulus of elasticity in bending (MOE) (TS 2478 same ISO 3349), Janka-hardness [(cross-section, parallel, perpendicular to grain) (Hj)] (TS 2479 same ISO 3350), impact bending strength (σ_i) (TS 2477 same ISO 3348) and tension strength perpendicular to grain ($\sigma_{z\perp}$) (TS 2476 same ISO 3346).

The number of specimens taken from each log was equal. Specimens were divided into nine treatment groups and for each group, a total of 30 test and 30 control samples were used. The samples were subjected to heat treatment at 120, 150 or 180°C for 2, 6, or 10 h in a small heating unit controlled to within ±1°C under atmospheric pressure.

Then the specimens were conditioned at 20 ± 2°C with 65% relative humidity according to TS 642 (same ISO 554). The equilibrium moisture content of the samples were approximately 12 percent after conditioning.

The air-dry density of the samples was determined. The dimensions and weights of the samples were measured, and the oven-dry density of the samples was determined at 0.01 mm and 0.001 gr sensitivity.

After the oven-dry dimensions were determined, the samples were soaked in water (20 ± 2°C) almost for one week. When no changes in sample dimensions were observed, the dimensions were measured.

After acclimatization, mechanical properties of the European Hophornbeam wood were determined.

At the end of experiments, moisture contents (M) of specimens were measured according to TS 2471 (same ISO 3130) and the moisture content of specimen in which moisture content deviated from 12% determined. Then strength values were corrected (transformed to 12% moisture content) by using the following strength conversion equation:

$$\delta_{12} = \delta_m \_[1 + \alpha\ (M_2 - 12)]$$

where δ_{12} = strength at 12% moisture content (N/mm2), δ_m = strength at moisture content deviated from 12% (N/mm2), α = constant value showing relationship between strength and moisture content (α = 0.05, 0.04, 0.02, 0.025, 0.015, 0.04 and 0.025 for $\sigma_{c//}$, MOR, MOE, σ_i, $\sigma_{z\perp}$ and Hj respectively) M2 = moisture content during test (%).

Surface roughness of the samples was measured by using a profilometer (Mitutoyo Surftest SJ-301). The surface roughness of the samples was measured with the profile method using a stylus device standard. The measuring speed, pin diameter, and pin top angle of the tool were 10 mm/min, 4 µm, and 90^0, respectively. The points of roughness measurement were randomly marked on the surface of the samples. Measurements were made in the direction perpendicular to the fiber of the samples.

Three roughness parameters, mean arithmetic deviation of profile (Ra), mean peak-to-valley height (Rz), and maximum roughness (Ry) were commonly used in previous studies to evaluate surface characteristics of wood and wood composites including veneer (Stombo, 1963). Ra is the average distance from the profile to the mean line over the length of assessment. Rq is the square root of the arithmetic mean of the squares of profile deviations from the mean line. Rz can be calculated from the peak-to-valley values of five equal lengths within the profile while maximum roughness (Ry) is the distance between peak and valley points of the profile which can be used as an indicator of the maximum defect height within the assessed profile (Mummery, 1993). Therefore, such parameters which are characterized by (ISO 4287) and (DIN 4768) were recorded.

Specification of this parameter is described by Hiziroglu (1996) and Hiziroglu and Graham (1998). Roughness values were measured with a sensitivity of 0.5 µm. The length of scanning line (Lt) was 15 mm and the cut off was λ = 2.5 mm. The measuring force of the scanning arm on the surfaces was 4 mN (0.4 g), which did not put any significant damage on the surface according to Mitutoyo Surftest SJ-301 user manual (Anonymous, 2002). Measurements were performed at room temperature and the pin was calibrated before the tests. Figure 1 shows the Mitutoyo Surftest SJ-301.

For the oven-dry density, air-dry density, swelling, compression strength parallel to grain, bending strength, modulus of elasticity in bending, Janka-hardness (cross-section, parallel and perpendicular to grain), impact bending strength, tensile strength perpendicular to grain and average roughness, all multiple comparisons were first subjected to an analysis of variance (ANOVA) and significant differences between mean values of control and treated samples were determined using Duncan’s multiple range test.

RESULTS AND DISCUSSION

Table 1 shows the oven-dry and air-dry densities and swelling ratios under the different treatment regimes. It is evident from Table 1 that the oven-dry density and air-dry density values decrease with increasing temperature and heat treatment time under the conditions used. Heat treated wood samples at a temperature of 180°C for 10 h gave the lowest air-dry and oven-dry density values when compared with other conditions studied.

Decreases in oven-dry density, air-dry density, and swelling to radial, tangential and longitudinal directions were found to be 10.03, 10.16, 48.71, 45.301 and 35.05% respectively, when treated at 180°C for 10 h. A decrease in swelling results in an increase in dimensional stability, which is required for several uses of wood.

These results can be explained with material loses in the cell wall, extractive substances and hemicellulos degradation due to applied height temperature. It is known that the weight of wood material and its swelling decreases when heat treatment is applied. Heat treatment lowers water uptake and wood cell wall absorbs less water because of the decrease of the amount of wood’s hydroxyl groups. As a consequence of the reduced number of hydroxyl groups, the swelling and shrinking were lower (Yildiz et al., 2006).

Surface roughness decreased by up to 21.52% in the sample heat-treated at 180°C for 10 h when compared with the control samples. This increase in smoothness is very important for many applications of solid wood. In addition, losses occurring in the planing machine are reduced and high quality surfaces are attained. It may be concluded that the heat treatment resulted a plastification on the solid wood surfaces. High temperatures above

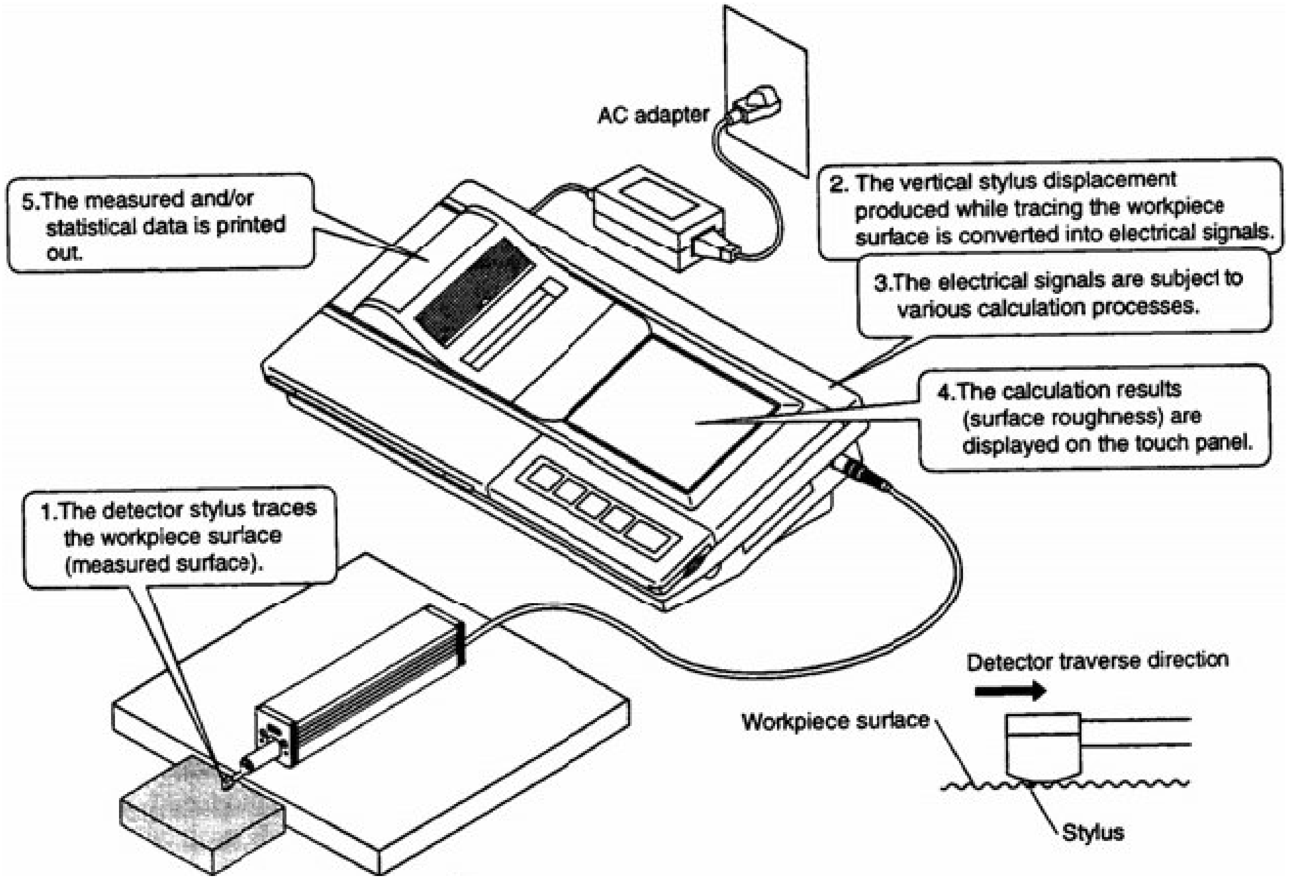

Figure 1. Schematic description of the Mitutoyo Surftest SJ-301.

160℃ cause change in lignin to a thermoplastic condition and thus to densify and compact solid wood surface (Follrich et al., 2006, Ayrilmis, 2009).

Also, the wooden materials with rough surface requires much more sanding process compared to one with smooth surface, which leads to decrease in thickness of material and, therefore, increase the losses due to the sanding process (Dundar et al., 2008). Table 3 shows the results of compression strength paralel to grain, bending strength, modulus of elasticity in bending, janka-hardness, impact bending strength, and tension strength perpendicular to grain, for the control and all the different heat treatment and time combinations. According to the averages, all the parameters decreased with increasing temperature and time. It is evident from the results that these values were all lower in heat-treated samples than in control samples. The effect of the heat treatments was significant for all the variables analyzed.

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 between each control and its test.

It is clear from this study that the value of all measured physical and technological properties and surface roughness decreased with increasing temperature and duration. Tables 2 and 4 show the percentage decrease of values in relation to the control for each treatment and each measured parameter.

The parameters measured varied in their rates of decrease with some experiencing a gradual loss and others exhibiting more dramatic changes (Figures 2 and 3). Heat treatment resulted in varying amounts of weight loss, depending on the treatment temperature and time.

The maximum decreases for all parameters were recorded at the treatment of 180℃ for 10 h. The lowest compression strength values obtained was 61.159 N/mm^2, total loss compared to the control was calculated to be 48.286%. Similarly, the lowest bending strength values were also obtained for samples treated at 180℃ for 10 h (111.643 N/mm^2). The bending strength loss, compared to the control was 45.515. The lowest modulus of elasticity in bending values was again obtained for samples treated at 180℃ for 10 h (12065.502 N/mm^2). The decrease in modulus of elasticity in bending was 42.478%. The lowest impact bending strength values was for samples treated at 180℃ for 10 h (5.066 J/cm^2). The loss of impact bending strength when compared to controls, was 72.481%. The lowest tensile strengths perpendicular to grain values were at 180℃ for 10 h (4.425

Table 1. The effect of heat treatment for different durations on physical properties and surface roughness in European Hophornbeam (*Ostrya carpinifolia* Scop.) wood.

Heat Treatment	Times	Unit	Oven-dry Density	Air-dry Density	Surface Roughness				Swelling		
			Do (g/cm^3)	D_{12} (g/cm^3)	Ra (µm)	Ry (µm)	Rz (µm)	Rq (µm)	Radial (%)	Tangential (%)	Longitudinal (%)
Control		Avg.	0.863	0.893	7.277	69.398	56.132	9.893	9.532	13.902	0.766
			A	A	A	A	A	A	A	A	A
		± s	0.036	0.024	1.469	10.751	13.018	2.130	1.783	2.135	0.257
		s^2	0.001	0.0005	2.158	115.60	169.42	4.540	3.179	4.558	0.066
		V	4.238	2.689	20.186	15.492	23.193	21.536	18.71	15.358	33.54
		N	30	30	30	30	30	30	30	30	30
120℃	2 h	Avg.	0.803	0.819	7.238	63.781	47.577	9.784	7.047	11.188	0.716
			BFGHIK	B	ABCDE	A	B	ABCDE	BGHIK	BFGHIK	ACDEFG
		± s	0.021	0.016	1.5	17.251	9.873	2.035	1.493	1.667	0.242
		s^2	0.0004	0.0002	2.250	297.59	97.494	4.142	2.229	2.781	0.059
		V	2.722	1.956	20.724	27.047	20.753	20.802	21.19	14.906	33.8
		N	30	30	30	30	30	30	30	30	30
	6 h	Avg.	0.798	0.817	7.205	63.025	47.453	9.437	6.946	11.164	0.672
			CIK	C	ABCDE	A	C	ADE	CHIK	CFGHIK	AFG
		± s	0.014	0.069	1.721	16.467	11.353	2.312	0.809	1.714	0.249
		s^2	0.0001	0.004	2.964	271.12	128.97	5.346	0.654	2.939	0.062
		V	1.765	8.530	23.897	26.128	23.926	24.501	11.64	15.357	36.99
		N	30	30	30	30	30	30	30	30	30
	10 h	Avg.	1.793	0.816	6.525	62.032	47.247	9.390	6.693	10.926	0.665
			DK	D	A	A	D	ADE	DK	DHIK	AFG
		± s	0.020	0.018	1.866	13.655	12.871	2.023	1.647	0.850	0.241
		s^2	0.0004	0.0003	3.482	186.46	165.62	4.096	2.713	0.723	0.058
		V	2.599	2.316	28.598	22.013	27.242	21.552	24.61	7.783	36.31
		N	30	30	30	30	30	30	30	30	30
150℃	2 h	Avg.	0.791	0.813	6.480	61.627	47.148	8.760	6.623	10.607	0.632
			EK	E	A	A	E	A	EK	EHIK	BG
		± s	0.017	0.023	1.908	16.185	6.507	2.425	0.691	2.132	0.201
		s^2	0.0002	0.0005	3.641	261.97	42.349	5.884	0.478	4.547	0.04
		V	2.154	2.861	29.445	26.263	13.802	27.689	10.44	20.103	31.81
		N	30	30	30	30	30	30	30	30	30
	6 h	Avg.	0.789	0.812	6.371	62.555	46.134	8.654	6.516	10.012	0.589
			F	F	A	A	F	A	FK	FIK	C
		± s	0.022	0.021	1.442	15.899	9.031	2.517	1.377	1.740	0.201
		s^2	0.0005	0.0004	2.079	252.82	81.566	6.335	1.895	3.028	0.040
		V	2.886	2.645	22.632	25.417	19.576	29.084	21.13	17.381	34.01
		N	30	30	30	30	30	30	30	30	30
	10 h	Avg.	0.787	0.804	6.242	60.891	45.768	8.364	6.245	9.96	0.586
			G	G	B	B	G	B	GK	GIK	D
		± s	0.023	0.020	1.755	16.958	10.580	2.246	1.587	2.655	0.207
		s^2	0.0005	0.0004	3.083	287.57	111.92	5.045	2.519	7.049	0.043
		V	2.976	2.565	28.129	27.850	23.118	26.855	25.42	26.65	35.36
		N	30	30	30	30	30	30	30	30	30

Table 1. contd.

180°C	2 h	Avg.	0.785	0.803	5.93	59.386	45.287	8.212 C	6.015	9.079	0.552
			H	H	C	C	H	2.183	HK	HK	E
		± s	0.021	0.019	1.590	12.560	10.654	4.766	1.443	1.878	0.185
		s^2	0.0004	0.0003	2.529	157.73	113.51	26.584	2.082	3.526	0.034
		V	2.762	2.370	26.820	21.150	23.526	30	23.99	20.68	33.51
		N	30	30	30	30	30		30	30	30
	6 h	Avg.	0.781	0.802	5.824	58.430	44.466	7.845	5.916	8.413	0.525
			I	I	D	D	I	D	IK	I	F
		± s	0.025	0.022	1.345	11.384	7.789	1.777	1.41	1.857	0.182
		s^2	0.0006	0.0005	1.809	129.60	60.673	3.158	1.989	3.449	0.033
		V	3.255	2.793	23.095	19.483	17.517	22.653	23.84	22.08	34.72
		N	30	30	30	30	30	30	30	30	30
	10 h	Avg.	0.777	0.801	5.711	55.181	41.906	7.738	4.889	7.604	0.498
			K	K	E	E	K	E	K	K	G
		± s	0.025	0.046	1.170	10.940	9.082	1.706	0.83	1.204	0.17
		s^2	0.0006	0.002	1.370	119.61	82.497	2.911	0.689	1.451	0.029
		V	3.235	5.748	20.498	19.826	21.673	22.051	16.98	15.84	34.15
		N	30	30	30	30	30	30	30	30	30

Avg = average; ± s =standard deviation; s2=variance. V= coefficient of variation. N= number of samples used in each test.
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 between each control and its test.

Table 2. Percentage decrease of physical properties and surface roughness in European Hophornbeam (*Ostrya carpinifolia* Scop.) wood following heat treatment for different durations.

Heat treatment	Time (h)	Oven-dry density	Air-dry density	Swelling			Surface roughness			
				Radial	Tangential	Longitudinal	Ra	Ry	Rz	Rq
		%	%	%	%	%	%	%	%	%
120°C	2 h	6.969	8.283	26.062	19.519	6.578	0.536	8.094	15.241	1.108
	6 h	7.533	8.491	27.123	19.693	12.33	0.998	9.182	15.462	4.616
	10 h	8.068	8.635	29.784	21.405	13.23	10.34	10.61	15.829	5.087
150°C	2 h	8.363	8.988	30.517	23.699	17.52	10.95	11.2	16.006	11.45
	6 h	8.59	9.057	31.634	27.979	23.04	12.45	9.861	17.811	12.53
	10 h	8.842	10.03	34.485	28.352	23.59	14.23	12.26	18.464	15.46
180°C	2 h	9.082	10.07	36.896	34.694	28.04	18.52	14.43	19.32	17
	6 h	9.54	10.09	37.928	39.482	31.51	19.97	15.8	20.783	20.71
	10 h	10.03	10.16	48.71	45.301	35.05	21.52	20.49	25.343	21.78

N/mm^2). The loss of tensile strength perpendicular to grain was 43.623%. Maximum hardness loss was obtained for samples treated at 180°C for 10 h; cross-section 23.375%, radial 51.931% and tangential 45.275%.

The compression strength and modulus of elasticity in bending values are greatly affected by initial treatments but after that only show a gradual decrease with increasing temperatures and treatment times. In contrast the strength values do not start to show significant changes with the lower temperature treatment of 120°C but an increase in temperature starts to have an effect.

In general the results of this study on the effect of heat treatment on European Hophornbeam are compatible with the findings in literature on the effect of heat treatment on different tree species.

A study on both spruce (*Picea orientalis* L.) and beech (*Fagus orientalis* L.) heated at 200°C for 6 h resulted in a 36% decrease in compression strength. On the other hand, a slight increase in compression strength was observed at 130°C for 6 h. In the same study, it was emphasized that compression strength was affected less by temperature increase compared to other strength properties. The highest decrease in modulus of elasticity for spruce was found to be 41.5% at 200°C for 6 h. On the

Table 3. The effect of heat treatment for different durations on mechanical properties in European Hophornbeam (*Ostrya carpinifolia* Scop.) wood.

Heat Treatment	Times	Unit	Compression Strength	Bending Strength	Modulus of Elasticity in Bending	Janka Hardness			Impact Bending	Tension Strength Perpendicular to Grain
						Cross-Section	Radial	Tangential		
			N/mm^2	N/mm^2	N/mm^2	N/mm^2	N/mm^2	N/mm^2	J/cm^2	N/mm^2
None		Avg.	118.266 A	204.906 A	20975.506 A	129.801 A	108.636 A	109.713 A	18.410 A	7.850 A
		± s	9.813	36.159	3176.552	10.883	16.411	14.239	16.529	1.658
		s^2	96.297	1307.537	10090.487	118.450	269.337	202.759	20.353	2.751
		V	8.297	17.647	15.144	8.384	15.106	12.978	14.663	21.130
		N	30	30	30	30	30	30	30	30
120°C	2 h	Avg.	110.184 BGHIK	200.563 ABCDEF	20140.898 BGHIK	110.19 BHIK	73.666 BDEFGHIK	70.26 BIK	7.576 BFGHIK	7.402 ABCDEFG
		± s	10.027	48.446	3520.203	10.335	21.785	11.863	2.183	1.340
		s^2	100.544	2347.058	12391.834	106.824	474.587	140.754	4.767	1.797
		V	9.100	24.155	17.477	9.379	29.572	16.885	28.821	18.114
		N	30	30	30	30	30	30	30	30
	6 h	Avg.	107.952 CGHIK	199.97 ABCDEF	20007.48 CGHIK	106.806 CHIK	72.276 CDEFGHIK	69.756 CIK	6.956 CHIK	7.332 ACDEFG
		± s	22.774	50.086	2242.860	10.156	23.579	16.030	1.990	1.3
		s^2	518.673	2508.609	5030424	103.159	555.999	256.986	3.961	1.692
		V	21.096	25.046	11.210	9.509	32.624	22.981	28.613	17.741
		N	30	30	30	30	30	30	30	30
	10 h	Avg.	107.297 DGHIK	190.583 ABCDEF	19155.913 DIK	106.15 DHIK	64.18 DIK	69.59 DIK	6.918 DHIK	7.202 ADEFG
		± s	11.298	41.970	3341.103	11.907	12.346	9.832	2.482	1.382
		s^2	127.658	1761.501	11162.975	141.787	152.445	96.673	6.163	1.912
		V	10.530	22.02	17.441	11.217	19.237	14.128	35.882	19.199
		N	30	30	30	30	30	30	30	30
150°C	2 h	Avg.	106.019 EK	184.533 ABCDEF	18977.737 EIK	104.473 E	63.136 EIK	68.08 EIK	6.655 EIK	6.680 BEFG
		± s	8.765	47.434	2313.481	11.445	10.274	8.667	2.058	1.134
		s^2	76.831	2250.064	5352198.3	130.991	105.565	75.132	4.237	1.286
		V	8.267	25.705	12.190	10.955	16.273	12.731	30.930	16.976
		N	30	30	30	30	30	30	30	30
	6 h	Avg.	104.141 FK	143.296 BCDEF	18533.783 FIK	104.45 F	59.683 F	66.87 FIK	6.341 FK	6.544 CEFG
		± s	7.106	38.282	2970.056	10.398	7.942	12.465	2.000	1.507
		s^2	50.503	1465.514	8821236.9	108.134	63.087	155.395	4.000	2.271
		V	6.824	26.715	16.025	9.955	13.308	18.641	31.539	23.031
		N	30	30	30	30	30	30	30	30
	10 h	Avg.	98.978 GK	120.220 C	18068.527 GK	104.02 G	59.153 G	66.596 GIK	5.900 G	6.285 DFG
		± s	9.798	16.822	4033.790	9.155	7.703	8.637	1.916	1.464
		s^2	96.011	282.990	16271.468	83.819	59.347	74.614	3.672	2.144
		V	9.899	13.992	22.324	8.801	13.023	12.970	32.477	23.300
		N	30	30	30	30	30	30	30	30

Table 3. contd.

180°C	2 h	Avg.	98.759	119.95	17541.572	99.976	58.7	66.396	5.778	5.689
			HK	D	HK	H	H	HIK	HIK	EFG
		± s	21.454	28.042	2227.046	10.777	7.814	10.296	1.816	1.006
		s^2	460.280	786.354	4959736	116.162	61.068	106.023	3.301	1.013
		V	21.723	23.378	12.695	10.780	13.312	15.507	31.445	17.697
		N	30	30	30	30	30	30	30	30
	6 h	Avg.	97.927	118.843	16523.52	99.956	54.336	60.043	5.31	4.724
			IK	E	I	I	I	I	I	F
		± s	21.949	30.169	2651.081	10.786	8.666	8.348	1.593	0.847
		s^2	481.791	910.181	7028230.2	116.343	75.107	69.700	2.540	0.717
		V	22.414	25.385	16.044	10.790	15.949	13.904	29.995	17.935
		N	30	30	30	30	30	30	30	30
	10 h	Avg.	61.159	111.643	12065.502	99.46	52.22	60.04	5.066	4.425
			K	F	K	K	K	K	K	G
		± s	4.194	32.097	2330.357	12.316	7.046	8.351	1.641	0.812
		s^2	17.590	1030.223	5430566.6	151.687	49.647	69.740	2.694	0.659
		V	6.857	28.749	19.314	12.383	13.493	13.90	32.398	18.352
		N	30	30	30	30	30	30	30	30

Avg = average; ± s =standard deviation; s^2=variance. V= coefficient of variation. N= number of samples used in each test. 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 between each control and its test.

Table 4. Percentage decrease of mechanical properties in European Hophornbeam (*Ostrya carpinifolia* Scop.) wood following heat treatment for different durations.

Heat Treatment	Times	Compression Strength	Bending Strength	Modulus of Elasticity in Bending	Janka Hardness			Impact Bending Strength	Tension Strength Perpendicular to Grain
					Cross-Section	Radial	Tangential		
		%	%	%	%	%	%	%	%
120°C	2 h	6.833	2.119	3.978	15.108	32.189	35.960	58.849	5.709
	6 h	8.721	2.409	4.615	17.715	33.469	36.4189	62.217	6.598
	10 h	9.275	6.990	8.674	18.220	40.922	36.570	62.419	8.255
150°C	2 h	10.355	9.942	9.524	19.512	41.882	37.947	63.852	14.905
	6 h	11.943	30.067	11.640	19.530	45.061	39.050	65.555	16.640
	10 h	16.308	41.329	13.858	19.861	45.549	39.299	67.951	19.935
180°C	2 h	16.493	41.461	16.371	22.976	45.966	39.481	68.615	27.526
	6 h	17.197	42.001	21.224	22.992	49.983	45.272	71.137	39.823
	10 h	48.286	45.515	42.478	23.375	51.931	45.275	72.481	43.623

other hand, a slight increase (8.4%) in modulus of elasticity was observed at 130°C for 10 h treated samples. For beech, heat treatment at 200°C for 10 h resulted in an increase in modulus of elasticity (39%). The lowest bending strengths for beech and spruce were observed when the wood samples were treated at 200°C for 6 h and 10 h. The decrease was 63.9 and 63.6% for beech and 63.8 and 72.7% for spruce at 6 and 10 h respectively. The greatest decrease in hardness values was observed when beech and spruce samples were treated at 180°C for 10 h. For beech samples, 25.9, 45.1 and 41.8% decrease in hardness was observed for cross-section, radial direction and tangential direction, respectively. For spruce 19.7, 43.0 and 42.5% decrease was observed for cross-section, radial direction and tangential direction, respectively (Yildiz, 2002).

A similar study was conducted by Gunduz et al. (2008) with Camiyanı Black Pine (*Pinus nigra* Arn. subsp. *Pallasiana* var. *pallasiana*). Decreases in swelling to radial, tangential and longitudinal directions were found to be 34.460, 51.738 and 27.360% respectively, when treated at 180°C for 10 h. Surface roughness decreased by up to

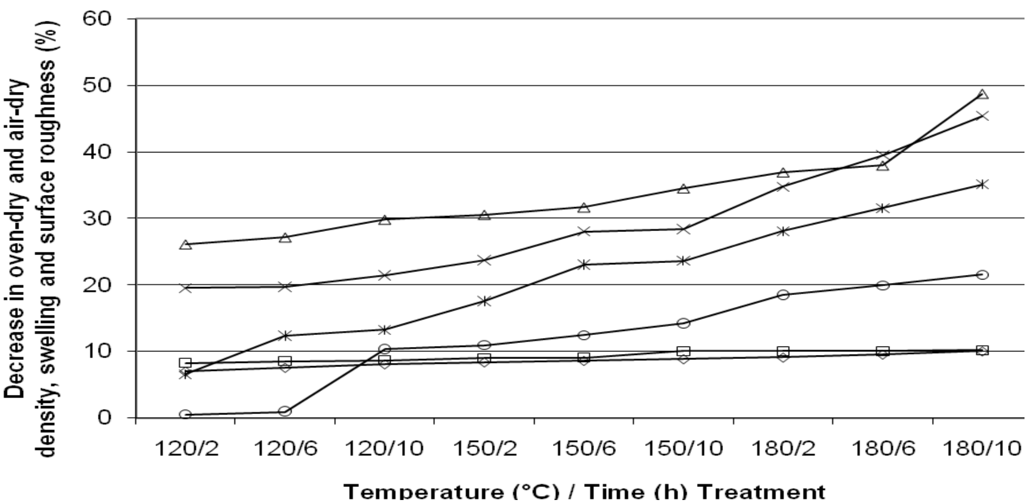

Figure 2. Percentage decrease of physical properties in European Hophornbeam (*Ostrya carpinifolia* Scop.) wood following heat treatment for different durations. (◊) oven-dry density; (□) air-dry density; (Δ) radial swelling; (x) tangential swelling; (*) longitudinal swelling; (o) surface roughness (Ra).

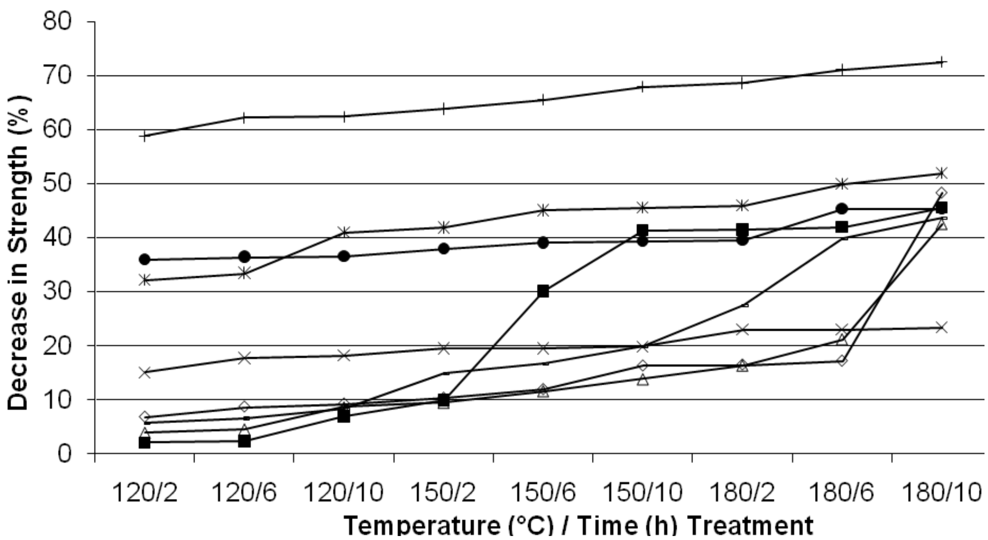

Figure 3. Percentage decrease of technological properties in European Hophornbeam (*Ostrya carpinifolia* Scop.) wood following heat treatment for different durations. (-) compression strength; (■) bending strength; (Δ) modulus of elasticity in bending; (*) Janka-hardness cross-section; (x) Janka hardness radial; (o) Janka-hardness tangential; (◊) impact bending strength; (●) tension strength perpendicular to grain.

15.71% in the sample heat-treated at 180℃ for 10 h when compared with the control samples. The low-est compression strength values obtained was 41.432 N/mm^2, total loss compared to the control was calculated to be 27.2%. Maximum hardness loss was obtained for samples treated at 180℃ for 10 h; cross-section 32.4%, radial 38.91% and tangential 24.2%.

Similarly another study showed that for Red-bud maple (*Acer trautvetteri* Medw.) wood, the lowest compression strength values obtained was 50.904 N/mm^2, total loss compared to the control was calculated to be 32.297%. Similarly, the lowest bending strength values were also obtained for samples treated at 180℃ for 10 h (92.423 N/mm^2). The bending strength loss, compared to the con-trol was 31.8%. The lowest modulus of elasticity in bending values was again obtained for samples treated at 180℃ for 10 h (8755.584 N/mm^2). The decrease in modulus of elasticity in bending was 28.330%. The lowest impact bending strength values was for samples treated at 180℃ for 10 h (3.520 J/cm^2). The loss of impact bending strength when compared to controls, was 42.972%. The lowest tensile strengths perpendicular to grain values were at 180℃ for 10 h (2.131 N/mm^2). The loss of tensile strength perpendicular to grain was 46.563 %. Maximum hardness loss was obtained for samples treated at 180℃ for 10 h; cross-section 31.256%, radial 54.171% and tangential 51.182% (Korkut et al., 2008).

Unsal et al. (2003) reported that in Turkish river red gum (*Eucalyptus camaldulensis* Dehn.) wood samples the largest hardness loss was at 180℃ for 10 h treatment. The loss was 23.91% cross-sectionally, 44.20% radially, and 33.57% tangentially. Unsal and Ayrilmis (2005) also found that the maximum compression strength parallel to grain decrease in Turkish river red gum (*Eucalyptus camaldulensis* Dehn.) wood samples was 19.0% at 180℃ for 10 h treatment.

Korkut (2008) found that the maximum compression strength parallel to grain decrease in Uludag Fir (*Abies bornmuellerinana* Mattf.) wood samples was 29.41 at 180℃ for 10 h treatment. Similarly, the lowest bending strength values were also obtained for samples treated at 180℃ for 10 h (60.565 N/mm^2). The bending strength loss, compared to the control was 29.28%. The lowest modulus of elasticity in bending values was again obtained for samples treated at 180℃ for 10 h (6379.62 N/mm^2). The decrease in modulus of elasticity in bending was 40.08%. The lowest impact bending strength values was for samples treated at 180℃ for 10 h (15.137 J/cm^2). The loss of impact bending strength when compared to controls, was 39.24%. The lowest tensile strengths perpendicular to grain values were at 180℃ for 10 h (24.658 N/mm^2). The loss of tensile strength perpendicular to grain was 28.14%. Maximum hardness loss was obtained for samples treated at 180℃ for 10 h; cross-section 22.43%, radial 23.27% and tangential 16.19%.

Esteves et al. (2007) reported that in *Pinus pinaster* and *Eucalyptus globulus* wood samples in the absence of air by steaming, inside an autoclave heated at 190 - 210℃ for 2-12 h treatment resulted the equilibrium moisture content decreased by 46% for pine and 61% for eucalyptus, the dimensional stability increased (maximum anti-shrinking efficiency in the radial direction of 57 and 90% for pine and eucalypt, respectively) and the surface wettability was lowered. Mass losses increased with treatment time and temperature reaching 7.3% for pine and 14.5% for eucalypt wood. The wood behaviour with moisture was improved.

The decreases in the strength properties can be explained by the rate of thermal degradation and losses of substance after heat treatments. The decrease in strength is mainly due to the depolymerization reactions of wood polymers (Kotilainen et al., 2000). The primary reason for the strength loss is the degradation of hemicelluloses, which are less resistant to heat than cellulose and lignin.

Changes in or loss of hemicelluloses play key roles in the strength properties of wood heated at high temperatures (Hillis, 1984).

Conclusıon

The smallest decrease was determined at the heat treatment of 120℃ for 2 h. In this research, technological strength values all decreased with increasing time and temperature treatments. The largest decrease found was for impact bending strength, followed by radial hardness, compression strength parallel to grain, bending strength, tangential hardness, tensile strength perpendicular to grain, modulus of elasticity in bending and cross-section hardness, when heat treated at 180℃ for 10 h under the conditions stated.

Heat treatment of wood causes a reduction of hygroscopicity, which gives less swelling, shrinkage and enhanced fungal resistance compared with un-treated wood, thus making it a more durable material and an alternative for wood with added preservatives in exterior applications (Tjeerdsma et al. 1998;Kamden et al. 1999).

The improved characteristics in swelling and surface roughness of heat-treated timber have to be balanced against the decrease in strength values when evaluating the effectiveness of using this treatment. Strength losses can be limited through alternative modified heat treatment techniques. Through heat treatment various tree species can be utilized using proper heat treatment techniques without any loses in strength values in areas, where woodworking and stability are important. Also, through heat treatment wood species with no commercial value can be used in areas where they had no use previously.

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