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INFLUENCE OF COMBINED HEAT TREATMENT AND DENSIFICATION ON MECHANICAL PROPERTIES OF POPLAR WOOD

Gonca Düzkale Sözbir[1], İbrahim Bektaş[1,♣], Ayşenur Kiliç Ak[1]

ABSTRACT

In this study, influence of combined heat treatment and densification on mechanical properties of poplar wood (*Populus usbekistanica*) such as density, EMC, compression strength, modulus of elasticy, modulus of rupture and static bending strength were investigated. Poplar samples were subjected to a temperature of 120°C, 160°C and 200°C for 1 and 3h. After the heat treatment, the heat treated samples were compressed in a hot press at a temperature of 120°C, press pressure of 5 MPa and press time of 30 minutes for densification. The results showed that the heat treatment affected the densification with increasing density. Additionally, the heat treatment decreased modulus of rupture (MOR), modulus of elasticity (MOE) and impact bending strength (IBS) with increasing temperature for undensified poplar wood. In conclusion, densification process has improved all the mechanical tested properties.

Keywords: Bending strenght, compression strength, density, EMC, *Populus usbekistanica*.

INTRODUCTION

Heat treatment is an effective method for improving the properties, dimensional stability and the durability of wood (Seborg *et al.* 1953, Kollmann and Scheiner 1963, Burmester 1973, Bourgois *et al.* 1998, Hill 2006, Gunduz *et al.* 2009). Besides being an eco-friendly process, modifications of wood decrease the hygroscopic irregularity (Navi and Sandberg 2012). Modifying the properties of wood using heat treatment is not a new method, it has been worked over centuries. Even in 1920, Tiemann reported that the high temperature drying decreased equilibrium moisture content and swelling of wood. Kollmann 1936, used high temperature and hot-press densification and called this process ''Lignostone'' and Seborg *et al.* (1945) generated a similar product called ''Staypack'' (Esteves and Pereira 2009).

Exposing heat treatment of wood makes it more fragile and rigid, so its mechanical strength decreases (Poncsak *et al.* 2006, Korkut *et al.* 2008, Korkut and Bektas 2008). Meanly, while the higher heat treatment temperature cause the lower the level of absorbed moisture and equilibrium moisture content (Tiemann 1920, Kollmann and Schneider 1963, Aydemir 2007), the wood becomes more brittle, and its mechanical strength and technological properties decrease in relation to the level of heat treatment (Gunduz *et al.* 2007). Most important parameters of heat treatment are temperature and holding time, but temperature has a greater effect on many wood properties than treatment time (Kartal *et al.* 2007). There have been some studies about this topic in literature. For example, according to Kol (2010) the heat-terated pine and fir's impact bending strength decreased by 63% and 9%, respectively. Moreover, Korkut and Hiziroglu (2009) also evaluated the effect of heat treatment on impact bending strength and founded that increasing treatment temperature and duration decreased impact bending strength.

The densification of wood is defined as a procedure entailing compression process after heated wood. Densification makes it possible for low-density and commercially uninteresting wood species to be transformed

[1]Kahramanmaras Sutcu Imam University, Faculty of Forest, Deparment of Forest Industrial Engineering, Kahramanmaras. Turkey
♣Corresponding author: ibtas63@yahoo.com
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into high performance and high value products (Kutnar *et al.* 2012). Since increasing the density of wood enhances its strength properties, there have been many studies on the densification of wood. In a study conducted by Kariz *et al.* (2017), spruce wood, thermally treated at 170°C, 190°C, 210°C and 230ºC were surface densified by compression at a temperature of 150ºC for 2 minutes. According to results, while mass loss increased with increasing temperature, equilibrium moisture content (EMC) decreased. Moreover, densification treatment increased value of modulus of rupture (MOR) and modulus of elasticity (MOE) but increasing heat temperature decreased these values. Ulker *et al.* (2012) noted that thermomechanical densification at 120°C, 140°C and 160ºC (6 MPa) increased density of scots pine wood by 93%, but press temperature did not effect ratio of density. MOE and MOR of scots pine increased at 120ºC, but then these values decreased at increasing temperature. In another study, test samples were prepared from Scots pine (*Pinus sylvestris* L.) wood exposed to heat treatment at 130°C, 145°C, 160°C, 175°C, 190°C and 205ºC for 3, 6, 9 and 12 hours. MOR and MOE values of samples were also decreased with increasing treatment temperature and end of heat treatment at 205°C decreased by 50% (Yapici *et al.* 2013).

The focus of the present study was to indicate the effects of combined heat treatment and densification on the mechanical properties of poplar wood and evaluate the differences between these properties. The density, mass loss and equilubrium moisture content of surface densified wood without heat treatment were determined. Thus, the study included an assesment of the various mechanical properties of poplar wood, including compression strength, modulus of elasticity and modulus of rupture, impact bending strength.

MATERIALS AND METHODS

Test specimens

Test specimens were obtained from poplar wood (*Populus usbekistanica*) lumbers supplied in Kahramanmaraş territory from Turkey. Compression strength parallel to grain specimens 20×20×30 mm, static bending strength and elastic modulus of bending specimens 20×20×360 mm as well as impact bending strength specimens 20×20×300 mm of sizes, were prepared for the laboratory experiment according to TS 2595 (1977), TS 2474 (1976) and TS 2477 (1976), respectively.

Heat treatment application

Specimens which had on average 10% moisture were heat treated at a temperature of 120ºC, 160ºC and 200ºC during 60 and 180 minutes in the presence of air. During heat treatment application, 100 ml -water vapour was given to prevent cracks until the temperature reaches 100ºC in oven. After reaching this temperature, vapour was removed and specimens were kept in oven until reaching target temperatures (120ºC, 160ºC and 200ºC). At the end of the heat treatment, the moisture of the samples became completely dry (0%).

Densification process

Before densification process, heat treated samples were conditioned in a test cabinet with a relative humidity of 65% and a temperature of 20ºC for 3 weeks in order to avoid damage of the samples during the densification process. Thus, moistures were increased up to 5-7% by waiting for a while in the test cabinet. Thereafter, samples were pressed at 120ºC under 5 MPa pressure during 30 minutes in absence of vapour. After 30 minutes samples were cooled down in the press for 10 minutes without opening. To calculate D_0, the pressurized samples were again dried in an oven at 103±2°C.

The sample codes

The sample codes generated according to the applied operations are shown in Table 1.

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Table 1: The sample codes and applied processes.

Samples Codes	Applied Processes				
	Heat treatment		Densification		
	Temperature (°C)	Duration (h)	Compression (MPa)	Temperature (°C)	Duration (h)
CS	-	-	-	-	-
HT11	120	1	-	-	-
HT13	120	3	-	-	-
HT21	160	1	-	-	-
HT23	160	3	-	-	-
HT31	200	1	-	-	-
HT33	200	3	-	-	-
HTD11	120	1	5	120	1/2
HTD13	120	3	5	120	1/2
HTD21	160	1	5	120	1/2
HTD23	160	3	5	120	1/2
HTD31	200	1	5	120	1/2
HTD33	200	3	5	120	1/2
DS	-	-	5	120	1/2

CS: Control sample, DS: Densified sample, HT: Heat treated, HTD: Heat treated densified.

Mechanical properties

The mechanical strength properties were determined according to the relevant standards are as follows Table 2.

Table 2: The mechanical strength properties.

Tests	Standards
Compression strength parallel to grain (CSP)	1
Static bending strength (MOR)	2
Modulus of elasticity in static bending (MOE)	3
Impact bending strength (IBS)	4

[1]TS 2595. 1977. Wood-determination of ultimate stress in compression parallel to grain, TSE, Ankara.

[2]TS 2474. 1976. Wood-determination of ultimate strength in static bending, TSE, Ankara.

[3]TS 2478. 1976. Wood-determination of modulus of elasticity in static bending, TSE, Ankara.

[4]TS 2477. 1976. Wood-determination of impact bending strength; Turkish Standart Institute, Ankara Turkey.

Other calculations

The values of the compression ratio, oven dry density, equilibrium moisture content and mass loss were determined by the assumption that they would contribute to the evaluation of the data of the mechanical properties calculated under different conditions. The compression ratio (CR), oven dry density (D_0), mass loss (ML) and equilibrium moisture content (EMC) were calculated by Equation 1, Equation 2, Equation 3 and

Equation 4 givens below:

$$CR(\%) = \frac{\text{Compressed thickness}(mm)}{\text{Initial thickness}(mm)} \times 100 \quad (1)$$

$$D_0\left(kg/m^3\right) = \frac{\text{Oven dry weight}(kg)}{\text{Oven dry volume}\left(m^3\right)} \quad (2)$$

$$ML(\%) = \frac{\text{First weight}(g) - \text{Last weight}(g)}{\text{First weight}(g)} \times 100 \quad (3)$$

$$EMC(\%) = \frac{\text{Wet weight}(g) - \text{Oven dry weight}(g)}{\text{Wet weight}(g)} \times 100 \quad (4)$$

Where; wet weight of samples were calculated after they reached constant weight at 65% rH and 20°C in the test cabinet.

Statistical analyzes

The results were analysed using one-way ANOVA from the SPSS statistical software program and Duncan's mean separation test to populate homogeneity groups that showed significant differences at the 95% confidence level.

RESULTS AND DİSCUSSİON

The results of the ANOVA and Duncan's mean separation tests for the oven-dry density (D_0), mass loss percentage (ML), equilibrium moisture content (EMC) and compression strenght parallel to grain (CSP) values measured in the test and statistical analysis are shown in Table 3.

Table 3: Average values of D_0, ML, EMC and CS in poplar wood specimens before (undensified) and after densification process.

Sample codes	CR (%)	D_0 (kg/m³)	ML (%)	EMC (%)	CSP (MPa)
CS	-	330 (20)(*)a(**)	-	9,81 (0,24)g	35,6 (2,54)a
HT					
HT11	-	332 (20)a	0,26 (0,23)ab	10,88 (0,19)h	34,6 (3,02)a
HT13	-	326 (20)a	0,71 (4,61)abc	9,87 (0,23)g	35,2 (2,13)a
HT21	-	333 (20) a	0,34 (0,20)ab	9,74 (0,20)g	36,2 (2,40)a
HT23	-	328 (20) a	1,24 (0,34)bc	9,76 (0,29)g	36,9 (2,29) ab
HT31	-	327 (20) a	3,48 (1,56)d	7,98 (0,32)c	39,7 (2,88)b
HT33	-	319 (20) a	5,19 (2,10)e	7,30 (0,28)b	39,8 (2,53)b
HTD					
HTD11	35	928 (50)de	0,53 (0,27)abc	8,56 (0,19)e	67,3 (6,98)f
HTD13	37	850 (40)c	0,68 (0,56)abc	8,77 (0,26)ef	59,0 (5,75)d
HTD21	34	947 (5)e	0,47 (0,29)abc	8,09 (0,19)cd	64,0 (7,65)e
HTD23	35	951 (40)e	1,56 (0,42)c	8,22 (0,37)d	63,5 (8,24)e
HTD31	34	807 (110)b	3,43 (0,97)d	6,79 (0,17)a	55,3 (9,42) d
HTD33	39	817 (60)b	5,74 (0,81)d	7,51 (0,27)b	51,1 (8,36)c
DS	36	919 (80)d	-	8,90 (0,28)f	76,3 (9,10)g
Probability		$p<0{,}001$	$p<0{,}001$	$p<0{,}001$	$p<0{,}001$

(*)The values in parentheses indicate standard deviation, (**)Mean values followed by the same lowercase letter are not significantly different (according to Duncan's mean separation test).

Data obtained from Table 3 showed that, heat treatment effect on compression strength, equilibrium moisture content and mass loss values, forming a significant difference (p<0,001) between heat treated (HT) and heat treated densified (HTD) poplar wood specimens. Concurrently, heat treatment effect on HT specimens was quite low (0,6%) when compared to control samples densities. Whereas, the highest decrease percentage in densities was measured in HT33, the maximum increase was obtained in HT21. In the light of these evaluations it can be said that heat treatment applied to the specimens prior to densification process has not got a significant impact on density. While heat treatment decreased the average density of densified specimens in the ratio of 4%, average density values of densified samples (DS) and HTD samples increased in the order of 178% and 167%.The highest density value was reached in HTD21 and HTD23. According to these data, heat treatment temperature had an impact on wood density in densified poplar wood. Densified poplar wood density calculated at a temperature of 200°C (HTD31, HTD33) was decreased in comparison with obtained values in other heat treatment temperatures.

Whereas, densification process did not cause mass loss, heat treatment caused mass loss depending on increasing temperature and heat duration. At temperature of 200°C, 160°C and 120°C, average mass loss values in undensified specimens were calculated as of 4,3%; 0,8% and 0,5% and related values in densified specimens as 4,6%; 1%, 0,6%; respectively. These values indicated that mass loss resultant 200°C was higher than those of 120°C and 160°C.

Compared to control samples, while avarage EMC values in samples subjected to 120°C increased 6%, 160°C and 200°C decreased 1% and 22%, respectively. In here, the highest decrease in EMC values were obtained in HTD31 and HTD33 (Table 3). Similarly, wood veneer specimens made with aspen (*Populus tremuloides*) and hybrid poplar clone were densified using heat, steam, and pressure at 140°C, 160°C, 180°C, 200°C and 220°C temperature (steam pressure of 550 kPa) by Fang *et al.* (2012) and they found that increasing temperature decreased value of EMC.

In previous studies CSP values were decreased with the increasing temperature (Sulzberger 1955, Manriquez and Moraes 2010, Zhong *et al.* 2016). For, in this study CSP values has increased in HT samples (Figure 1a). This can be explained by the decrease in the holocellulose ratio (7%), which is the result of mass loss due to the increase in temperature (Bektas *et al.* 2017). At the same time, as can be seen from Table 3, the effect of temperature on the CSP is statistically different between 120 and 200°C samples according to Duncan test. Here, the reduction of EMC values was also effective. Comparing the CSP values of HTD samples with the CS, a remarkable increase (68,6%) was observed after densification process. Meanwhile, CSP values of HTD samples increased averagely 61,96% than HT samples. At the same time, CSP values of DS samples increased by 114% compared to CS. Also, Ulker *et al.* (2012) densified scots pine specimens by thermomechanical densification process using 120°C, 140°C and 160°C under 6 Mpa pressure. They determined that compression strength values increased with the densification process in densified scots pine specimens; however, it decreased with the increase of press temperature. In yet another study, pine and fir wood exposed to thermowood process at a temperature of 212°C and 190ºC for 2 hours, Kol (2010) stated that compression strength values increased 4% and 17%, respectively.

Table 4 shows the MOE and MOR values of densified and undensified poplar wood specimens with and without heat treatment calculated based on D_0, ML, EMC values.

Table 4: The mean values of MOE and MOR tests.

Sample codes	CR (%)	D_0 (kg/m^3)	ML (%)	EMC (%)	MOE (MPa)	MOR (MPa)
CS	-	325(20)(*)ab(**)	-	9,01 (0,94)f	5693 (286)a	59,02(2,99)c
HT						
HT11	-	337 (20)b	0,41 (0,45)a	7,53 (0,26)c	5960 (580)a	59,9(4,94)c
HT13	-	340 (30)b	1,22 (0,18)ab	7,55 (0,27)c	5918 (432)a	59,8(3,31)c
HT21	-	334(20)b	2,27 (0,22)cd	7,63 (0,23)c	5727 (476)a	58,1(4,18)c
HT23	-	333 (20)b	2,65 (0,17)de	8,13 (0,23)d	5931 (368)a	58,3(2,36)c
HT31	-	297 (20)a	9,40 (1,77)h	5,42 (0,16)a	5178 (441)a	41,2(6,72)b
HT33	-	311(30)ab	10,76 (2,40)i	5,49 (0,22)a	5107 (540)a	33,4(10,95)a
HTD						
HTD11	35	778 (50)e	1,40 (0,13)bc	8,50 (0,28)e	12117(1057)e	89,1(12,13)ef
HTD13	37	791 (60)ef	1,20 (0,13)ab	8,46 (0,26)e	11931(1271)de	91,7(8,51)f
HTD21	34	819 (70)f	2,42 (0,21)d	7,98 (0,21)d	12015 (733)e	91,1(7,96)f
HTD23	35	676 (80)cd	3,30 (1,96)ef	7,72 (0,18)c	11110(916)c	82,8(8,19)e
HTD31	34	696 (80)d	4,21 (0,81)f	7,02 (0,26)b	11174(901)cd	74,8(12,33)d
HTD33	39	656 (90)c	5,71 (1,08)g	6,91 (0,89)b	9768 (2,017)b	57,5(15,26)c
DS	36	708 (80)d	-	8,42 (0,27)e	13105 (1168)f	101,3(13,71)g
Probability		p<0,001	p<0,001	p<0,001	p<0,001	p<0,001

(*)The values in parentheses indicate standard deviation, (**)Mean values followed by the same lowercase letter are not significantly different (according to Duncan's mean separation test).

Data in Table 4 revealed that HT and HTD poplar wood samples densities increased until 200ºC. As for the decreasing in 200ºC, it can be explained by degradation of the chemical components occuring when the poplar woods were exposed to above 160ºC (Bektas *et al.* 2017). Likewise, Boonstra *et al.* (2007a) reported a decrease in density of heat-treated Scots pine and Norway spruce (< 200°C) by 10% and 8,5%, respectively. Compared control samples of both process, it can be seen that densification process increased oven-dry density about 118%. The most notable decrease in density of HTD samples was measured at HTD23 and above temperatures compared to DS (708 kg/m^3).

Table 4 shows that average mass loss values at 200°C, 160°C and 120°C tempereatures in HT samples calculated as of 10,1%; 2,5% and 0,8% and related values in HTD samples as 5%; 2,9%; 1,3%, respectively. The EMC value of the control group was 9,01%. Also, the EMC values of poplar samples decreased after HT and HTD processes. This decrease occurred proportionate with directly mass loss. Accordingly, it can be deduced that increases in mass loss can decrease EMC value.

MOE values of DS were found to be 130% increased in comparison with CS. While MOE values of HT samples subjected to 120ºC and 160ºC increased, this value decreased in samples exposed to 200ºC (Figure 1c). Besides, MOE of HTD samples decreased with increasing heat treatment temperature and duration as seen in Figure 1c. Comparing the MOR values of DS with CS, after densification process, an increase of MOR values by 72% was detected. The MOR values of heat treated poplar wood samples increased at 120°C, but decreased at high temperatures (Figure 1b). In other words, densification process increased MOR values, however; it was understood from Table 4 that increasing the applied heat treatment temperature and duration caused decrease of MOR values. A great number of researchers stated that MOE and MOR values of wood showed slight increase in low temperature and short-term heat treatment application (Bekhta and Niemz 2003, Poncsak *et al.* 2006, Shi *et al.* 2007). However; it has been emphasized that heat treatment applications with high temperature degrees decreased these values at varying rates. For instance, Kamdem *et al.* (2002), MOR and MOE of beech 40%, Bekhta and Niemz (2003) MOR of spruce 44-50%, Korkut *et al.* (2008), MOE and MOR of scots pine 27-33% ratios determined decrease. In another study, Cao *et al.* (2012) treated to Chinese fir at a temperature ranging from 170°C to 230°C and time from 1 to 5 hours and found that both MOE and MOR values increased under less than 200°C, but decreased above this temperature. Similarly, Poncsak *et al.* (2006) noted that heat-treated birch showed a reduction of MOR with increasing treatment temperature. It is well known that MOE properties of wood are correlated with density. It has also been confirmed by Percin *et al.* (2016) that the modulus of elasticity increases as the density increases.

Table 5: The analyses results of Impact bending strength test.

Sample codes	CR (%)	D0 (kg/m³)	ML (%)	EMC (%)	IBS (kJ/m²)
CS	-	339(40) (*)a	-	7,91(0,32)gh	034(0,05)cd
HT					
HT11	-	340(40)a	0,58(0,23)a	8,04(0,42)hı	35(0,08)cd
HT13	-	343(20)a	1,06(0,19)a	8,08(0,30)hı	41(0,09)def
HT21	-	328(10)a	2,26(0,24)bc	8,48(0,34)hı	31(0,07)c
HT23	-	331(20)a	3,03(0,30)c	7,53(0,36)f	27(0,06)bc
HT31	-	311(10)a	5,51(1,32)e	5,73(0,33)b	22(0,03)ab
HT33	-	318(40)a	10,15(2,23)g	5,29(0,21)a	16(0,03)a
HTD					
HTD11	35	797(60)d	0,72(0,20)a	8,16(0,30)ı	48(0,11)fg
HTD13	37	795(60)d	1,16(0,18)a	8,05(0,23)hı	47(0,11)fg
HTD21	34	797(60)d	2,15(0,16)b	7,78(0,27)g	45(0,10)efg
HTD23	35	692(80)b	3,00(0,41)c	7,21(0,60)e	43(0,15)efg
HTD31	34	757(70)c	4,39(0,39)d	6,86(0,36)d	39(0,09)de
HTD33	39	661(80)b	7,30(1,40)f	6,38(0,23)c	28(0,10)bc
DS	36	755(90)c	-	7,90(0,29)gh	50(0,06)g
Probability		p<0,001	p<0,001	p<0,001	p<0,001

(*)The values in parentheses indicate standard deviation, (**)Mean values followed by the same lowercase letter are not significantly different (according to Duncan's mean separation test).

Table 5 showed that effect of heat treatment on D_0 (kg/m³), ML (%), EMC (%) and IBS (kJ/m²) differed between HT and HTD samples. An increase in density value was observed when heat treatment duration raises from 1 to 3 hours at a temperature of 120°C for HT poplar wood. This is because, heat treatment with steam increased thermal conductivity of wood and the thermal conductivity increased density. Densification process has increased density of samples. Accordingly, density of DS demonstrated an increase about 123%.

The mass loss values had significant differences in 160°C and 200ºC for HT and HTD samples, but at 120ºC there is no statistical difference for both processes. As the process temperature and duration have increased, mass loss also increased for HT and HTD samples. According to Bourgois and Guyonnet (1988), the mass losses are quite high at higher temperatures. As seen in Table 5, there was no significant difference between the EMC values of the control groups and the samples treated at 120ºC, whereas significant differences have been observed between the HT and HTD samples depending on the duration at all other temperatures. Jamsa and Viitaniemi (2001) noted that the reason for the decrease of the EMC is that cell walls absorb less water after the heat treatment as a result of chemical changes in wood cells. Moreover, the decrease of the EMC owing to heat treatment leads to an improvement of dimensional stability (Esteves and Pereira 2009).

The IBS values of the control samples increased by an average of 47% after densification process. IBS values increased at 120ºC depending on the duration and density after heat treatment process. Additionally, IBS values decreased at temperature of 160ºC and above inverse proportion with the mass loss. On the other hand, the densification process increased the IBS value compared with HT samples (Figure 1d). However, as the temperature and application duration have increased, IBS values decreased for HTD samples. In a study conducted by Bal and Efe (2016) on the subject, it is stated that the applied heat treatment temperatures of 180°C, 200°C and 220ºC cause the IBS strength of *Fagus orientalis* wood to decrease by 31%; 62% and 72%, respectively. Also, Dundar *et al.* (2012) found that the increase in temperature reduces the IBS value of the black pine specimens as a result of the steam heat treatment applied at 180°C and 200°C for 3 hours. In a research performed with Scots pine, radiata pine and Norway spruce specimens, after heat treatment the impact strength showed a decrease (Boonstra *et al.* 2007a).

Table 6 shows the change percentages of mechanical properties of undensified and densified wood with and without heat treatment according to the control specimens.

Table 6: Changes of mechanical properties according to the application of heat treatment and densification processes.

Treatments	CSP (%)	MOE (%)	MOR (%)	IBS (%)
CS	-	-	-	-
HT11	-2,81	4,69	1,44	2,94
HT13	-1,12	3,95	1,37	5,88
HT21	1,69	0,60	-1,29	-8,82
HT23	3,65	0,14	-1,59	-20,59
HT31	11,52	-9,05	-30,16	-35,29
HT33	11,80	-10,29	-43,34	-52,94
HTD11	89,04	112,84	50,97	41,18
HTD13	65,73	109,57	55,29	38,24
HTD21	79,78	111,05	54,42	32,35
HTD23	78,37	95,15	40,24	26,47
HTD31	55,34	96,28	26,72	14,71
HTD33	43,54	71,58	-2,58	-17,65
DS	114,33	130,19	71,59	47,06

When Table 6 is examined in general, changes of CSP values in HT samples increased with increasing temperature, but in HTD samples these changes decreased. In contrast to temperature, changes of CSP values in HTD samples have inversely proportional with increasing duration. The maximum changes in CSP values were obtained in HT33 (12%) and HTD11 (89%) in both processes. In the literature, Boonstra *et al.* (2007a) found 28% and 8% increase on compressive strength parallel to the fibres and in tangential for heat-treated Scots pine, respectively.

As for the MOE and MOR changes in HT samples, values decreased at varying rates with increasing temperature and duration except for HT23. MOE changes ratio decreased from 112,84 to 96,28 for 1h temperature application in HTD samples. For 3h application values decreased from 109,57 to 71,58. Namely, the highest MOE values were reached in 1h application than 3h. In the MOR values, all values except HTD33 increased by varying rates (26,72-55,29%) in HTD samples compared to the control sample. In contrast to these results, Boonstra *et al.* (2007b) obtained a 6% reduction in bending strength, but a 17% increase on MOE in treated Norway spruce wood.

As it is also clear in Table 6 that IBS strength values decreased with the increase of temperature and duration in both processes except HT13. The maximum percentage decrease in general was measured in HT33 IBS value. Furthermore, IBS values increased at all temperatures in HTD samples except HTD33 compared to the control samples, while in HT samples IBS values decreased except HT13. This is because of the higher density in HT13 samples (343 kg/m^3).

Moreover, densification application increased the strength values of CSP, MOE, MOR and IBS by 114,33%; 130,19%; 71,59% and 47,06%, respectively. That is, as seen in Figure 1, densification process increased all the mechanical properties, however; only heat treatment application decreased strength values except compression strength at 200ºC. In addition to these assessments, it can be said that the unexpected deviations seen in Table 5 were caused by the changes in density and mass loss of the samples. Moreover, Jiang *et al.* (2009) stated that 160°C treatment temperature is probably enough to cause degradation lignin molecules, to change their position and harm the adhesive linkage of lignin with cellulose fibrils.

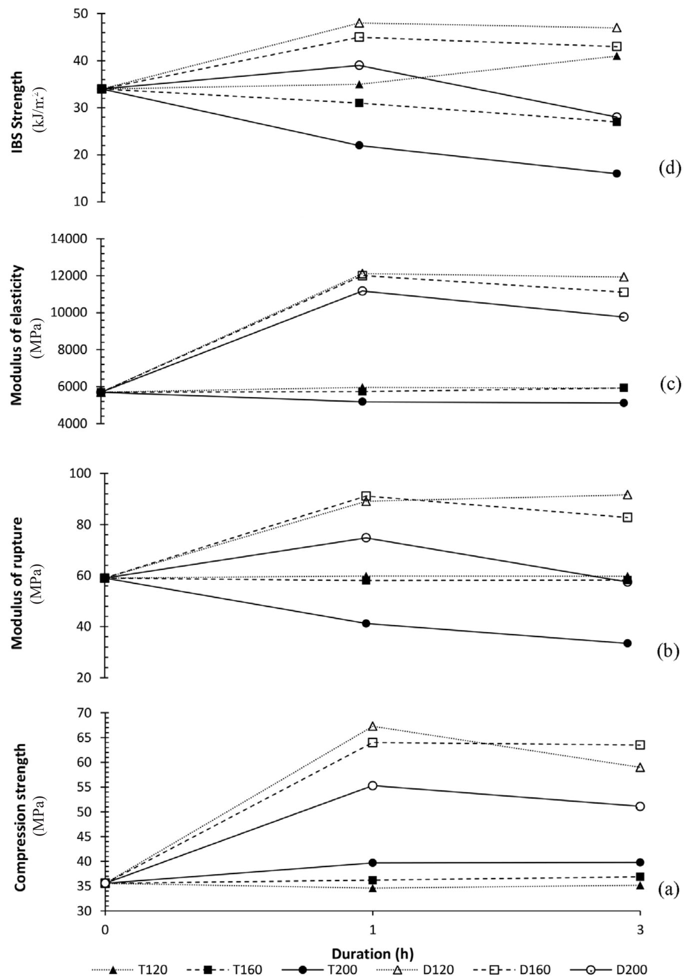

Figure 1: The strength-duration curves of mechanical strength values (a) compression strength, (b) modulus of rupture, (c) modulus of elasticity, (d) IBS) and durations.

When Figure 1 is examined, except for CSP, the other mechanical properties showed a decrease after the heat treatment. When the heat treatment times are taken into consideration, it is seen that the reduction in the mechanical properties of the samples subjected to the heat treatment for 3 hours is much more than that for the heat treatment for 1 hour.

By evaluating the same graph according to the heat treatment temperature, it is observed that as the temperature increases, the mechanical properties reduce parallel to the duration-related results, but this does not occur in the case of CSP samples subjected to only heat treatment. Instead, the CSP values increases as the temperature increases.

CONCLUSIONS

The main results obtained from this study can be summarized as follows. The density was influenced by heat treatment before densification and no homogeneous relationship has been determined between density and duration. The value of EMC generally decreased with increasing heat treatment temperature and densification at all mechanical tests specimens. In mechanical properties, the modulus of rupture, modulus of elasticity and impact bending strength were affected negatively by increasing heat treatment temperature. But, densification process generally increased the mechanical properties of poplar wood. Taking the effect of temperature and duration on mechanical properties into account, it was determined that in 200°C the effect of the duration on the mechanical properties was more notable in heat treated samples, while at the other temperatures the effect of them was close to each other.

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