Effects of Heat Post-Treatment on Dimensional Stability and Water Absorption Behaviours of Mechanically Densified Uludağ Fir and Black Poplar Woods

Hüseyin Pelit,[a] Mehmet Budakçı,[a,*] and Abdullah Sönmez [b]

One of the most persistent problems with mechanically densified wood is its inherent dimensional instability. The effects of heat post-treatment on the changes in spring-back (SB), compression ratio recovery (CRR), thickness swelling (TS), and water absorption (WA) of newly-tested Uludağ fir (*Abies bornmuelleriana* Mattf.) and black poplar (*Populus nigra* L.) wood samples that had been thermo-mechanically densified were investigated. Samples were densified with compression ratios of 25% and 50% with temperatures of 100 and 140 °C, respectively. Then, the heat post-treatment was applied to the samples at 185 and 212 °C for 2 h. For the two newly-tested wood types, results of the preliminary study show that SB and TS were higher at a 50% compression ratio compared with 25%. Regarding densification temperature, TS was lower in samples densified at 140 °C, while SB was higher. WA values were lower in compressed samples (50%) at high rates. The effect of the densification temperature on WA was insignificant. Heat post-treatment had a considerable effect on the dimensional stability and hygroscopicity of the densified Uludağ fir and black poplar samples. With an increase in heat treatment temperature, the dimensional stability increased, while the hygroscopicity of densified samples decreased. As a result of heat post-treatment applied at 212 °C, SB, CRR, TS, and WA decreased by 88%, 85%, 79%, and 53%, respectively.

Keywords: Densification; Heat treatment; Wood material; Dimensional stability; Water absorption

Contact information: a: Department of Wood Products Industrial Engineering, Faculty of Technology, Duzce University; 81620, Duzce, Turkey; b: Department of Wood Products Industrial Engineering, Faculty of Technology, Gazi University; 06500, Ankara, Turkey;
** Corresponding author: mehmetbudakci@duzce.edu.tr*

INTRODUCTION

Demand for qualified wood material in the wood products and furniture industries is increasing every day. There is a great deal of difficulty in finding wood material of high quality, and the great increase in the cost of materials makes it necessary to develop new or different modification methods in wood materials.

In recent years, there has been a rapid increase in the application of various modification methods to wood and wood materials to improve their properties. In particular, thermal, thermo-mechanical, and thermo-hydro-mechanical treatments of wood have been widely studied and applied to improve its properties (Bekhta *et al.* 2014a). It is well known that many of the properties of solid wood correlate with its density and can thus be enhanced by increasing the density (Sandberg *et al.* 2013). Wood is a porous material and, in theory, can be rather easily compressed until the density reaches that of the cell wall material (~1.50 g/cm³) (Rautkari *et al.* 2010). Compressing wood in the

transverse direction reduces the void volume of the lumens in the wood material and increases the wood density. This process is commonly called densification, *i.e.*, the untreated wood has been compressed under conditions that do not cause the lignin to flow. The main aim of wood densification is to improve the mechanical properties of wood by eliminating its porosity without the use of chemical additives (Sandberg *et al.* 2013; Laine *et al.* 2013). Moreover, depending on densification and post-treatment conditions, it has been stated in different studies that surface quality (smoothness, brightness, colour, hardness), wetting behaviour, and durability properties can be developed in densified wood material (Welzbacher *et al.* 2008; Ünsal *et al.* 2011; Arruda and Del Menezzi 2013; İmirzi *et al.* 2014; Bekhta *et al.* 2014a,b, 2015; Pelit *et al.* 2015a). The main detriment associated with densification in an open system is the fixation of the compressive deformation. Several approaches to fixing the compression-ratio of densified wood and reducing its recovery and dimensional instability are viable. These include impregnation with a synthetic resin, mechanical fixing and thermo-hydro-mechanical treatments at high temperature and moisture (Navi and Heger 2004; Laine *et al.* 2013). In addition, after mechanical densification, various heat post-treatments can be included (Dwianto *et al.* 1997; Welzbacher *et al.* 2008; Fang *et al.* 2011; Hill *et al.* 2012; Cai *et al.* 2013; Pelit *et al.* 2014; 2015b).

Heat treatment of wood is a commercially successful and effective method to improve the dimensional stability and durability against biodegradation. Heat treatment leads to permanent changes in the molecular structure of the chemical compounds of wood. The underlying fundamental idea for this application is to treat wooden material with temperatures greater than 150 °C. This is the range at which chemical reactions become accelerated (Boonstra *et al.* 2006; Boonstra 2008). As a result of such chemical change/degradation, the hygroscopicity and equilibrium moisture content (EMC) of heat-treated wood material decreases, and, consequently, dimensional stability and durability increase. Additionally, the wood color can be changed (Bekhta and Niemz, 2003; Esteves *et al.* 2007; Gündüz *et al.* 2008; Esteves and Pereira 2009; Aydemir *et al.* 2011; Aytin *et al.* 2015). During heat treatment, thermal degradation of the chemical compounds of wood occurs first in hemicelluloses and then in cellulose and lignin, respectively (Kamdem *et al.* 2002; Yang *et al.* 2007).

The main disadvantage of such heat treatments is the reduced strength properties of the end product based on mass loss and chemical degradation of wood (Bekhta and Niemz 2003; Yıldız *et al.* 2006; Korkut *et al.* 2008; Welzbacher *et al.* 2008; Gündüz *et al.* 2010; Pelit *et al.* 2015b; Perçin *et al.* 2015). Furthermore, during heat treatment, wood defects such as cracking (internal and/or surface cracks), collapsing and deformation (*e.g.*, bow, spring, twist, and cup) may occur because of the changes in the anatomical structure of wood (Boonstra *et al.* 2006).

Using the two important wood modification methods, *i.e.*, densification and heat treatment, together is especially important for the production of wood material with improved qualities. Therefore, the aim of this study was to determine the physical properties (spring-back, compression ratio recovery, thickness swelling, and water absorption) of densified and heat-treated Uludağ fir (*Abies bornmuelleriana* Mattf.) and black poplar (*Populus nigra* L.) woods, which have relatively low density. In addition, this study is of importance as a preliminary research testing the two newly-tested wood types by applying a combination of mechanical densification and heat post-treatment.

EXPERIMENTAL

Materials

In this study, Uludağ fir (*Abies bornmuelleriana* Mattf.) and black poplar (*Populus nigra* L.) woods, which have relatively low densities (Uludağ fir: 0.47 g/cm^3, black poplar: 0.58 g/cm^3), were utilized. Trees were supplied as round wood from a timber company in Düzce city in Turkey. Round woods were cut from their sapwood with an automatically controlled band saw. Cuts were determined by considering sample dimensions using annual rings parallel to the surface (tangent section), and these were transformed into timbers of a rough scale. Sampling methods and general requirements as stated in TS 2470 (1976) were complied with, and attention was paid to ensure that no rot, knots, cracks, or differences in colour or density were present in the samples. Samples were initially dried to approximately 12% moisture before being subjected to natural drying, and then they were brought to the dimensions given in Table 1.

Table 1. Draft Dimensions of Samples before Densification

Compression ratio (%)	Length - longitudinal direction (mm)	Width - tangential direction (mm)	Thickness - radial direction (mm)
Control	400	95	20
25	400	95	26.7
50	400	95	40

Before the densification process (according to TS 2471 (1976)), samples were kept on hold in a conditioning cabin with a relative humidity of 65 ± 3% and temperature of 20 ± 2 °C until they reached a stable weight. To prevent possible moisture changes that could occur after conditioning, samples were preserved in plastic bags until the time of densification.

Densification

Densification of the samples using a thermo-mechanical densification method was carried out with a hydraulic press machine with a 180 ton capacity, the capability of pressure and temperature control, and containing pressing tray dimensions of 60 × 60 cm^2. The densification process was done by forming four different variations at target compression ratios of 25% and 50%, with temperatures of 100 ± 5 and 140 ± 5 °C.

The samples were placed onto the bottom tray of the pressing machine and held under slight pressure. Heat transfer was achieved by placing the samples in contact with the heated bottom and top press tray (Fig. 1).

Fig. 1. (a) Heating of the samples before compression; (b) compression of the heated samples

The samples were kept in this position until their internal temperatures reached the target temperature, which was checked with a thermometer. Afterwards, a compression process in the radial direction with automatic control at 60 mm/min loading speed was carried out. To obtain the proposed compression thickness (20 mm), metal stopping sticks were placed onto the pressing tray at particular intervals. Compressed samples were held under pressure for 10 min. After this period, the samples were taken from the press machine and cooled to room temperature under a pressure of 5 kg/cm^2 to minimise spring-back effects.

Heat treatment

Heat treatment was performed on the experimental samples to provide dimensional stability with an electrically heated and air circulating furnace. Heat treatment was carried out in three stages (1, drying at elevated temperature; 2, heat treatment; 3, cooling and conditioning) and under the protection of the water vapor according to the methods described in the ThermoWood Handbook (2003). In the first stage, samples were dried to approximately 0% moisture by increasing the furnace temperature with heat and steam. In the second stage, heat, at the proposed temperatures (185 and 212 °C), was applied to the samples for 2 h. In the third stage (conditioning), the temperature was reduced, and the moisture ratio of the samples was brought to 4% to 6% by applying water spray.

After the heat-treatment process, samples remained at a temperature of 20 ± 2 °C and relative humidity of 65 ± 3% until they reached a stable weight (TS 2471 1976). Afterwards, samples were cut to dimensions of 30 × 20 × 20 mm (length-longitudinal direction × width-tangential direction × thickness-radial direction). However, the thickness (radial direction) of the samples used to determine spring-back and compression ratio recovery values was not cut again. The test samples were prepared to provide ten repetitions for each variable (n = 10).

Methods

Determination of spring-back and compression ratio recovery

Compressed wood has a tendency to partially regain its original shape after removal of applied pressure, which can be attributed to elastic recovery. After removal of press machine pressure, instantaneous spring-back, which is caused by the release of internal stresses, takes place. Additionally, moisture losses that occurred in the samples by the influence of temperature in compression caused a separate spring-back after the samples had been conditioned at 20±2 °C and at relative humidity (RH) of %65±3. The total spring-back (*SB*) values of the samples were determined using Eq. 1. Furthermore, compression ratio recovery (*CRR*) (or set recovery) values of the samples soaked to water at 20 ± 2 °C until they reached stable thickness were determined using Eq. 2 (Pelit *et al.* 2014),

$$SB = [(T_3 - T_2) / T_2] \times 100 \quad [\%] \tag{1}$$

$$CRR = [(T_4 - T_3) / (T_1 - T_3)] \times 100 \quad [\%] \tag{2}$$

where T_1 is the original thickness of samples before densification, T_2 is the thickness of samples under pressure (load), T_3 is the thickness of samples conditioned at 20 ± 2 °C and 65 ± 3% RH for three weeks, and T_4 is the thickness of samples after soaking in water for 672 h. Thicknesses were determined with a Vernier caliper with a sensitivity of ± 0.01 mm.

Determination of thickness swelling and water absorption

The thickness (radial direction) swelling and water absorption tests were carried out according to ISO 4859 (1982). Samples were kept at 103 ± 2 °C in a drying furnace for 24 h, and weight and thicknesses at this condition were determined at ± 0.01 sensitivity. Then, the samples were sunk into distilled water for 672 h. At the end of this period, the samples were removed from the water and the surface water was wiped off using blotting paper. Weight and thicknesses at this condition were determined again at ± 0.01 sensitivity. Thickness swelling (*TS*) and water absorption (*WA*) values were calculated using Eqs. 3 and 4,

$$TS = [(T_R - T_0) / T_0] \times 100 \quad [\%] \tag{3}$$

$$WA = [(M_R - M_0) / M_0] \times 100 \quad [\%] \tag{4}$$

where T_R is the thickness of samples after soaking in water, T_0 is the oven-dry thickness of samples, M_R is the weight of samples after soaking in water, and M_0 is the oven-dry weight of samples.

Statistical analysis

The MSTAT-C 2.1 package program (Michigan State University, USA) was used for statistical evaluation. Analysis of variance (ANOVA) tests were performed to determine the effect of heat post-treatment on the dimensional stability and water absorption behaviours of thermo-mechanical densified woods at the 0.05 significance level. When there was a significant difference between groups, Duncan's test was used for comparison.

RESULTS AND DISCUSSION

Analysis of variance results for spring-back (SB), compression ratio recovery (CRR), thickness swelling (TS), and water absorption (WA) measurements from samples densified and heat-treated are given in Table 2.

According to Table 2, the effect of wood type, densification, and heat treatment factors on SB, CRR, TS, and WA were found to be statistically significant ($P \leq 0.05$). Mono comparison results of the Duncan test conducted for the factors wood type, densification, and heat treatment are shown in Table 3.

Spring-back (SB)

According to the results of the comparisons in Table 3, SB was higher in black poplar samples (12.73%) than Uludağ fir samples (10.36%). With respect to densification conditions, the highest SB value (20.25%) was found in the samples densified under D4 conditions, while the lowest SB value (3.80%) was found in the samples densified under D1 conditions.

Regarding heat treatment level, the highest SB value (15.33%) was found to be in the samples without heat treatment and the lowest value (5.85%) was observed in the samples for which heat treatment was applied at 212 °C. The SB values of Uludağ fir and black poplar samples densified and heat treated are presented comparatively in Fig. 2.

Table 2. ANOVA Results for SB, CRR, TS, and WA

Tests	Factors	Degrees of freedom	Sum of squares	Mean square	F-value	Level of significance ($P \leq 0.05$)
SB	Wood type (A)	1	337.915	337.915	126.6682	.0000*
	Densification (B)	3	11215.147	3738.382	1401.3407	.0000*
	Heat treatment (C)	2	4031.430	2015.715	755.5951	.0000*
	Interaction (AB)	3	108.238	36.079	13.5244	.0000*
	Interaction (AC)	2	44.563	22.282	8.3523	.0003*
	Interaction (BC)	6	507.021	84.504	31.6763	.0000*
	Interaction (ABC)	6	27.690	4.615	1.7299	ns**
	Error	216	576.227	2.668		
	Total	239	16848.232			
CRR	Wood type (A)	1	1524.399	1524.399	151.4706	.0000*
	Densification (B)	3	1601.055	533.685	53.0292	.0000*
	Heat treatment (C)	2	270521.949	135260.975	13440.0956	.0000*
	Interaction (AB)	3	13.848	4.616	0.4587	ns**
	Interaction (AC)	2	901.227	450.613	44.7748	.0000*
	Interaction (BC)	6	1659.044	276.507	27.4749	.0000*
	Interaction (ABC)	6	36.412	6.069	0.6030	ns**
	Error	216	2173.822	10.064		
	Total	239	278431.756			
TS	Wood type (A)	1	69.043	69.043	25.4371	.0000*
	Densification (B)	4	61170.409	15292.602	5634.1366	.0000*
	Heat treatment (C)	2	48785.773	24392.887	8986.8849	.0000*
	Interaction (AB)	4	101.516	25.379	9.3502	.0000*
	Interaction (AC)	2	181.685	90.843	33.4684	.0000*
	Interaction (BC)	8	21726.126	2715.766	1000.5488	.0000*
	Interaction (ABC)	8	110.755	13.844	5.1006	.0000*
	Error	270	732.855	2.714		
	Total	299	132878.162			
WA	Wood type (A)	1	27282.494	27282.494	403.4972	.0000*
	Densification (B)	4	8666.494	2166.623	32.0435	.0000*
	Heat treatment (C)	2	128926.635	64463.317	953.3866	.0000*
	Interaction (AB)	4	542.617	135.654	2.0063	ns**
	Interaction (AC)	2	4288.018	2144.009	31.7090	.0000*
	Interaction (BC)	8	15325.544	1915.693	28.3323	.0000*
	Interaction (ABC)	8	1156.662	144.583	2.1383	.0326*
	Error	270	18256.073	67.615		
	Total	299	204444.537			

*Significant at 95% confidence level; **not significant

Table 3. Duncan's Test Results for Mean Values

Factors	SB (%)		CRR (%)		TS (%)		WA (%)	
	$\bar{x}$	*HG*	$\bar{x}$	*HG*	$\bar{x}$	*HG*	$\bar{x}$	*HG*
Wood type								
Uludağ fir	10.36	b	48.52	b	24.25	a*	116.91	a*
Black poplar	12.73	a*	53.56	a*	23.29	b	97.83	b
Densification								
Undensified	-	-	-	-	3.77	e	113.71	a*
D1	3.80	d	51.38	b	18.16	c	111.04	ab
D2	16.10	b	48.95	c	42.02	a*	102.62	c
D3	6.02	c	55.13	a*	16.77	d	109.95	b
D4	20.25	a*	48.70	c	38.13	b	99.53	d
Heat treatment								
Untreated	15.33	a*	96.10	a*	40.64	a*	135.52	a*
185 °C	13.44	b	41.46	b	20.85	b	100.37	b
212 °C	5.85	c	15.56	c	9.82	c	86.21	c

D1: 100 °C / 25%; D2: 100 °C / 50%; D3: 140 °C / 25%; D4: 140 °C / 50%; $\bar{x}$: Mean value; *HG:* homogeneous group; *the highest value

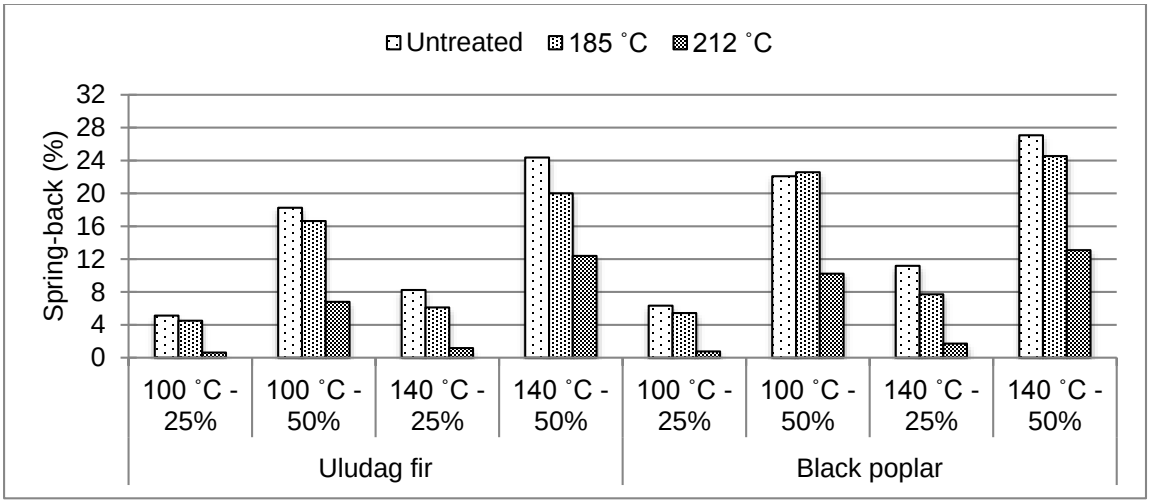

Fig. 2. Comparative appearance of spring-back (SB) values

According to Fig. 2, SB was higher in the black poplar samples than in the Uludağ fir samples under the same conditions. It was thought that initial densities and structural differences such as void volume (porosity), chemical composition, *etc*. of the wood materials had marked effects on the results. In materials where cell wall volume is high and void volume is low, internal stress, which occurs when the effects of heat and pressure are high during the compression process, causes an increase in SB (Pelit *et al*. 2014; Pelit and Sönmez 2015). It was observed that both the compression ratio and the compression temperature affected SB values. The SB was higher in samples densified at a high compression ratio (50%) and a high compression temperature (140 °C). As stated in previous studies, rapid tension ratio increases in the body of wood material together with increases in compression ratio and cause more internal stress in the material, thus affecting

the SB results (Wolcott *et al.* 1989; Nairn 2006; Laine *et al.* 2013; Pelit *et al.* 2014). Samples that were compressed at 140 °C had higher SB values than samples compressed at 100 °C. The cause of this was likely the occurrence of deformation changes (breaking, cracking, buckling, *etc*.) in the cell structure of the wood as a result of the compression and the amount of moisture remaining in the wood materials after thermo-mechanical densification. After densification, the mean moisture contents were 6.6% for samples densified at 100 °C and 3.2% for samples densified at 140 °C. In similar studies, a higher level of moisture loss and greater thickness increase was observed in Scots pine and Eastern beech samples densified at higher temperatures during the acclimatisation phase (20 ± 2 °C / 65 ± 3% RH) (Pelit *et al.* 2014; Pelit and Sönmez 2015). Moreover, deformations (breaking, cracking, *etc*.) arising in the cell structures when wood material is not sufficiently softened, occurred more frequently during densification carried out with compression (Kutnar and Sernek 2007; Pelit 2014). In addition, in mechanical compression at low temperatures, wood exhibits glassy behaviour; the formation of shear cracks and brittle polymers have been reported in wood when the hemicellulose and lignin are in a glassy state. Furthermore, it has been stated that when the temperature of the wood material is above that of the glass transition, the amorphous polymers in the cell structure can be re-arranged without a great amount of deformation and breakage (Kutnar and Sernek 2007). According to reports in the literature, these deformations occurring in cell structures as a result of compression, especially at a low temperature (100 °C), decrease the tendency of a cell to return to its previous form. Depending upon the temperature increase, the SB values decreased significantly following heat treatment. After heat treatment, the SB values decreased by up to 88% in both wood types, especially when compared to samples compressed at 25% without heat treatment. After heat treatment, the relaxation of internal stress occurring in wood material because of compression and the decrease in the equilibrium moisture content (EMC) of the samples can affect the results. The average EMC of samples were 8.3% at 185 °C and 6.5% at 212 °C. In previous studies, it was stated that SB effects on materials can be prevented by eliminating the internal stress in densified wood material and the hygroscopic components of the cell wall. Thermal degradation of hemicelluloses plays an especially important role in eliminating SB in wood materials (Dwianto *et al.* 1997; Morsing 2000; Heger *et al.* 2004).

Compression Ratio Recovery (CRR)

According to results in Table 3, CRR values obtained were higher in black poplar samples (53.56%) than Uludağ fir samples (48.52%). The highest CRR value (55.13%) found in the densification levels was obtained in the samples densified under D3 conditions, while the lowest values (48.70% and 48.95%) was obtained in the samples densified under D4 and D2 conditions. According to heat treatment levels, the highest CRR values (96.10%) were found in the samples without heat treatment, whereas the lowest value (15.56%) was obtained in the samples to which the heat treatment was applied at 212 °C.

The CRR values of Uludağ fir and black poplar samples densified and heat-treated are given comparatively in Fig. 3. As shown, CRR was found to be higher with a 25% compression ratio compared with a 50% compression ratio for both wood types. It was determined that differing densification temperatures did not have differing effects on CRR. It was observed that samples that were densified at low compression ratio (25%) had a higher tendency to return to their initial dimensions after a soaking test. In the literature, it was stated that at a high compression ratio, cell collapse and cell rupture are higher in

densified wood and lumens are partly closed (Ahmed *et al.* 2013; Pelit 2014; Bekhta *et al.* 2015). This specific case may prevent a cell from returning to its previous form.

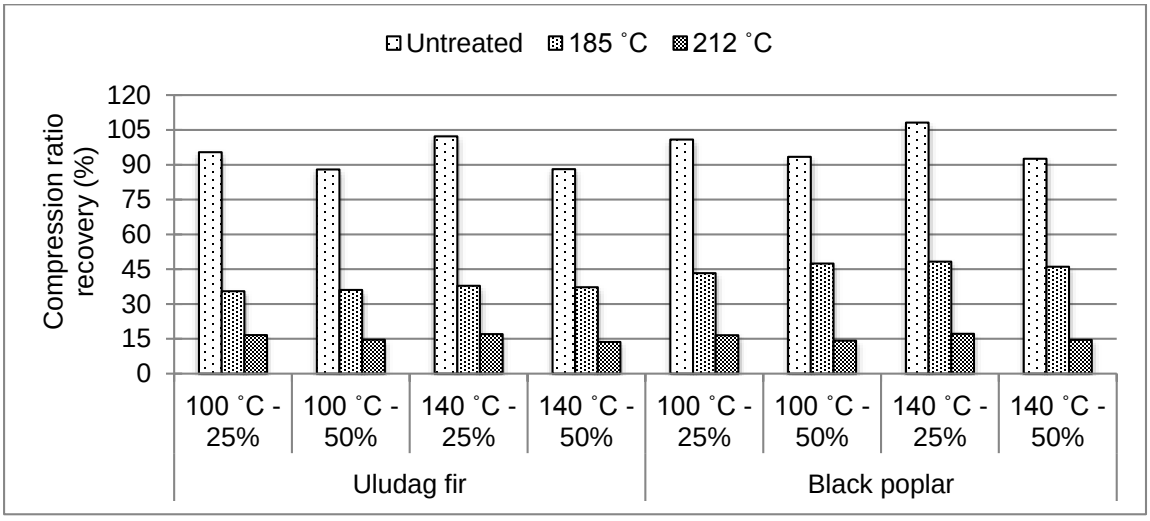

Fig. 3. Comparative appearance of compression ratio recovery (CRR) values

With heat treatment application, CRR decreased significantly, depending on temperature. As a result of heat treatment applied at 212 °C, CRR decreased up to 85% compared with control (untreated) samples. This situation can be explained by the relaxation of internal stresses formed in wooden material by heat treatment within the densification process. The destruction of cross-links that are responsible for the shape memory effect also results from heat treatment (Navi and Heger 2004; Inoue *et al.* 2008; Welzbacher *et al.* 2008; Dubey 2010; Laine *et al.* 2013; Pelit *et al.* 2014). Furthermore, it was stated that several factors had contributed to the increase in the dimensional stability of the wood *via* heat treatment. These included the loss of hygroscopic hemicellulose polymers during heat treatment leading to a decrease of the hydroxyl groups and the consequent reduction of the hygroscopic features, the cross-linking or bridging of cellulose chains as a result of the splitting of two hydroxyl groups on adjacent cellulose chains under high temperature conditions, and the cross-linking of the aromatic rings in the lignin (Kocaefe *et al.* 2015).

Thickness Swelling (TS)

According to results shown in Table 3, TS was higher in Uludağ fir samples (24.25%) than black poplar samples (23.29%). Regarding densification conditions, the highest TS value (42.02%) was found in samples densified under D2 conditions, and the lowest TS value (3.77%) was found in samples that were not densified. Regarding heat treatment levels, the highest TS value (40.64%) was found in samples without heat treatment, while the lowest value (9.82%) was obtained in samples heat-treated at 212 °C.

The TS values of Uludağ fir and black poplar samples that were densified and heat-treated are showed comparatively in Fig. 4. As shown, compared with samples that were not densified, more TS occurred in densified samples, depending on compression ratio. The increase in compression ratio influenced TS significantly. The highest TS was obtained at 50% compressed samples. In previous studies, it was stated that an important disadvantage of densification by compression is that the wood reverts in the direction of

its initial dimensions before compressing when soaked in water or exposed to high relative humidity. This situation is caused by the extension of the cell wall, relaxation of internal stresses formed in the material structure as a result of compression, and, in particular, the cell recovering to its original form (Seborg *et al.* 1956; Kollmann *et al.* 1975; Blomberg *et al*. 2006; Pelit *et al.* 2014, 2015b). Regarding densification temperature, higher TS was found in samples densified at lower temperature (100 °C). It can be stated that lower SB in these samples after densification may have an effect on results. After heat treatment, TS decreased significantly, especially in densified samples. TS decreased by up to 79% in both densified wood types, depending on heat treatment temperature. It can be said that heat treatment application (especially at high temperature) has an important effect on the dimensional stability of densified wood material.

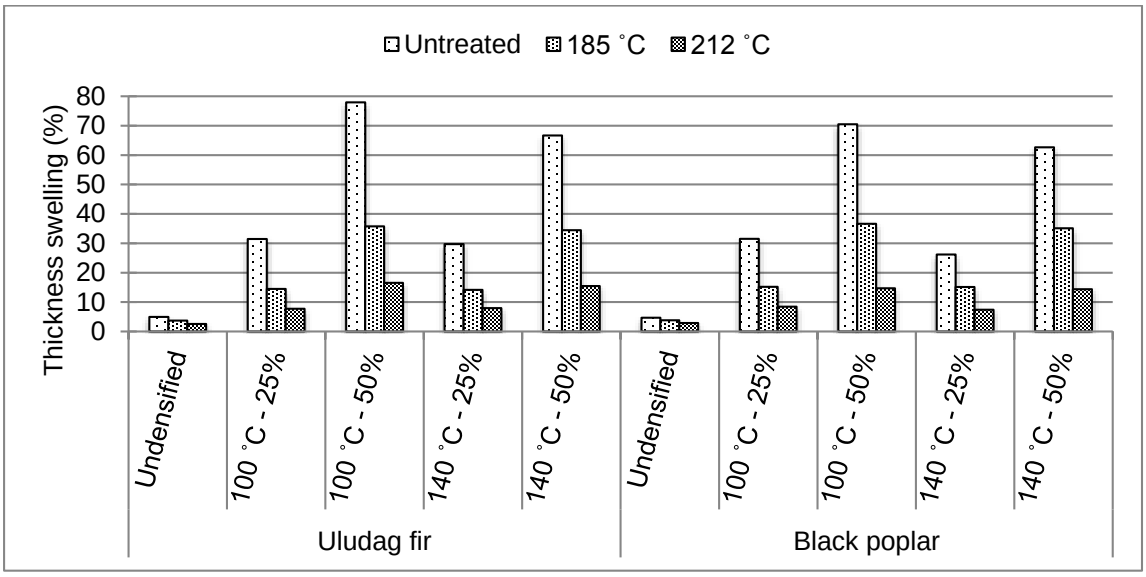

Fig. 4. Comparative appearance of thickness swelling (TS) values

Water Absorption (WA)

According to the results of the comparisons in Table 3, WA was higher in Uludağ fir samples (116.91%) than black poplar samples (97.83%). The highest WA (113.71%) at densification conditions level was obtained in the samples that were not densified, while the lowest WA (99.53%) was observed in samples densified under D4 conditions. With respect to heat treatment levels, the results for WA were the highest (135.52%) in samples without heat treatment and the lowest (86.21%) in samples heat-treated at 212 °C. The WA values of Uludağ fir and black poplar samples densified and heat-treated are given comparatively in Fig. 5.

According to the results shown in the figure, WA was higher in Uludağ fir samples than black poplar samples. It can be said that high black poplar sample density and low void volume have an effect on the results. WA was found to be higher in densified samples (especially with a compression ratio of 50%) compared with samples that were not densified. However, there was a contrary situation after heat treatment, and lower WA was obtained, especially in samples densified at high compression ratio (50%). It can be said that the decrease in void volume of densified samples and prevention of the swelling effect with heat treatment had an effect on the results.

As explained in the CRR section, lumen voids were partly closed in wood densified at a high compression ratio, which is thought to decrease WA. It was observed that the effect of densification temperature on WA was insignificant. After heat treatment, there was a decrease in the WA of samples, depending on treatment temperature. There was a 50% decrease in Uludağ fir samples heat-treated at 212 °C and up to a 53% decrease in black poplar samples. It can be said that changes in the chemical structure of wood materials with heat treatment application and the decrease in its hygroscopicity affected the results. In the literature, it was stated that the high temperature of heat post-treatment reduced the hygroscopicity of wood samples due to changes in the polar groups on the molecular structures of cellulose, hemicelluloses, lignin, and extractives (Laine *et al.* 2013; Morsing 2000). Furthermore, it was reported that there were specific permanent changes in the chemical and physical structures of wood materials with heat treatment application, including hydroxyl groups in wood materials decreasing or transforming into different forms (etherification, esterification) (ThermoWood Handbook 2003; Tjeerdsma and Militz 2005; Aydemir *et al.* 2011).

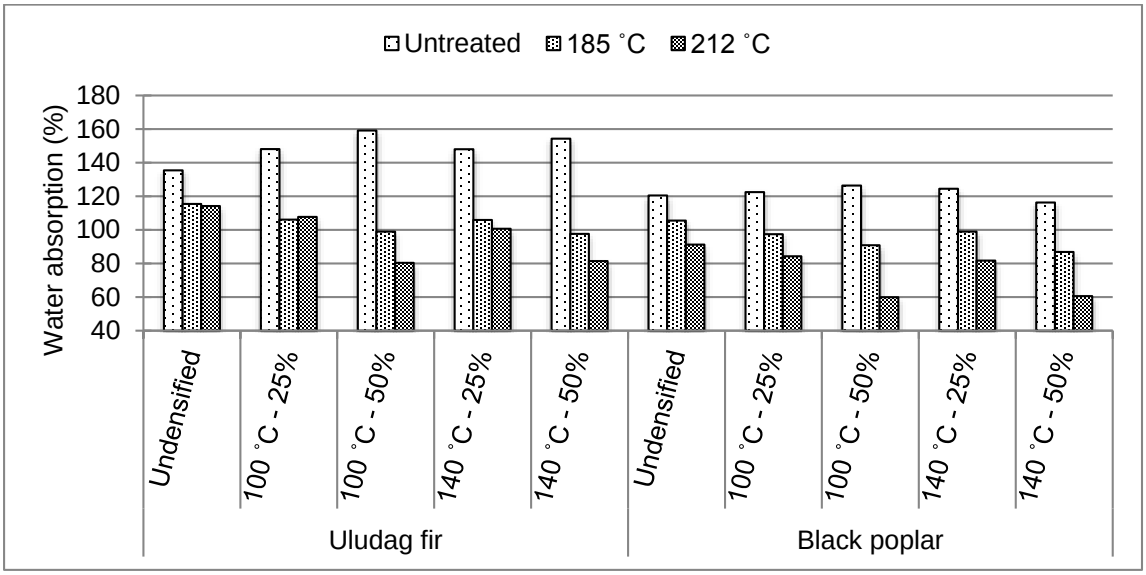

Fig. 5. Comparative appearance of water absorption (WA) values

CONCLUSIONS

1. The effects of heat post-treatment application on the dimensional stability and water absorption (WA) of thermo-mechanically densified Uludağ fir and black poplar woods was investigated. Spring-back (SB) values were higher in black poplar samples than in Uludağ fir samples. An increase in compression ratio caused an increase in both SB and thickness swelling (TS). Regarding densification temperature, SB was higher in samples compressed at 140 °C than in those compressed at 100 °C. TS was higher in Uludağ fir wood in which SB was lower and in samples densified at 100 °C.
2. WA values were higher in Uludağ fir samples with lower density compared with black poplar samples. Before heat treatment, WA was higher in samples compressed at a high ratio (50%). However, after heat treatment, WA was lower in samples compressed at

50% compared with those compressed at 25%. It was observed that the effect of densification temperature was not important for WA values.

3. In densified Uludağ fir and black poplar samples, heat post-treatment had a significant effect on dimensional stability and WA. The increase in the temperature of the heat post-treatment had a positive effect on results. As a result of the heat post-treatment applied at 212 °C, the SB, compression ratio recovery (CRR) effects, TS, and WA of densified samples decreased by up to 88%, 85%, 79%, and 53% respectively.

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