

Effect of Thermo-Vibro-Mechanic® Densification Process on the Gloss and Hardness Values of Some Wood Materials

Süleyman Şenol ^a and Mehmet Budakçı ^{b,*}

This study aimed to determine the gloss and hardness values of low-density wood materials densified using the Thermo-Vibro-Mechanic® (TVM) method after pretreatment with wood stain and wood preservative. This was carried out with a TVM density press that was designed and produced with the support of project 115O138 of the Scientific and Technological Research Council of Turkey (TUBITAK). The samples obtained from Uludağ fir (*Abies bornmüelleriana* Mattf.) and black poplar (*Populus nigra* L.) were pretreated with wood stain and wood preservative prior to the TVM densification process. The TVM densification operation was conducted at three different temperatures, three different vibration pressures, and three different vibration times. After the TVM densification process, changes in the gloss (ISO 2813 2014) and Brinell hardness values (TS 2479 1976) of the samples were determined. According to the results, the TVM densification method increased the gloss value of the Uludağ fir and black poplar wood pretreated with the wood preservative by 175% and 1390%, respectively, and increased the Brinell hardness value by 63% and 150%, respectively.

Keywords: Thermo-Vibro-Mechanic® (TVM) densification; Wood stain; Wood preservative; Gloss; Hardness;

Contact information: a: Department of Interior Architecture, Faculty of Architecture, Kütahya Dumlupınar University, Kütahya – Turkey; b: Department of Wood Products Industrial Engineering, Faculty of Technology, Düzce University; 81060, Düzce, Turkey;

* Corresponding author: mehmetbudakci@duzce.edu.tr

INTRODUCTION

In recent years, wood material has become an industrial material with increasing application thanks to technological developments. Human population growth and the rise in new wood applications increases the need for wood material and therefore causes the material with these superior properties to gradually decrease in availability. This suggests the necessity of a more efficient use of existing resources, such as the recycling of residual materials or the use of various types of commercially undesirable wood species with low-resistance properties in the industry through various modifications and producing various materials (Pelit 2014; Şenol *et al.* 2017).

The term “wood modification” is defined as the change or improvement of the negative properties of wood (Şenol and Budakçı 2016; Sandberg *et al.* 2017). Wood material with increased density can be an alternative to other structural materials (Blomberg and Persson 2004; Blomberg *et al.* 2005; Kutnar and Šernek 2007; Pelit *et al.* 2015; Şenol and Budakçı 2016). Most of the mechanical properties of wood material are related to density (Blomberg and Persson 2004; Kamke 2006; Kutnar and Šernek 2007; Rautkari 2012; Pelit *et al.* 2014; Budakçı *et al.* 2016; Pelit *et al.* 2018). Because densification of wood material increases the mechanical properties and hardness of the wood material, many experiments have been conducted to develop a suitable process (Blomberg and Persson 2004; Rautkari *et al.* 2011; Fang *et al.* 2012; Gaff and Gašparík

2013; Laine *et al.* 2014; Fu *et al.* 2017; Li *et al.* 2017; Şenol *et al.* 2017; Şenol and Budakçı 2018; Song *et al.* 2018).

Through densification, low-density wood materials are transformed into high-density and can be converted into commercially high-value products. High-density wood material types can also be made more resistant through densification (Blomberg *et al.* 2005; Kutnar and Šernek 2007; Ulker *et al.* 2012).

The material type, temperature, the softening or plasticizing period, the densification method, and the pressing pressure are the most important variables in the densification of wood material. By application of these variables, the mechanical properties of densified wood can be increased up to 100% (Ulker *et al.* 2012; Gao *et al.* 2019).

In the densification of wood material *via* compressing, densification is achieved by reducing the cell wall and reducing the pore space (Kutnar *et al.* 2009; Pelit 2014; Budakçı *et al.* 2016). Ruptures and cracks may occur in the cell wall of the compressed wood material under normal atmospheric conditions. The natural elastic structure of wood plays an important role in densification by compressing. If the wood temperature in densification is above the critical transition temperature, densification is achieved without major deformation and without cellular breaks in the amorphous polymers. The compression properties are mostly dependent on the density, humidity, cell wall volume of the wood, and the compression direction. The biggest problem encountered in densified wood materials by compression is that they tend to return to their initial dimensions due to spring-back when used in places exposed to contact with moisture or water (Seborg *et al.* 1956; Kollmann *et al.* 1975; Morsing and Hoffmeyer 1998; Kultikova 1999; Blomberg *et al.* 2006; Gong and Lamason 2007; Rautkari 2012; Pelit 2014). This can be resolved by a heat and vapor effect (Gong and Lamason 2007; Kutnar and Šernek 2007; Rautkari *et al.* 2010; Pelit 2014; Li *et al.* 2017).

Recently, heat treatment/thermal modification applications have started to eliminate the negative aspects of the densified wood. However, the temperature values above 150 °C used in these applications change the color and weight of the wood material and diminish its mechanical properties. This may restrict the use of wood material, especially as structural systems (columns, beams, flooring, *etc.*) (Bekhta and Niemz 2003; Esteves *et al.* 2007; Boonstra 2008; Korkut and Kocaefe 2009; Pelit 2014; Şenol *et al.* 2017; Şenol and Budakçı 2018).

In light of this information, this study aimed to obtain high quality wood material through improving the resistance properties of especially low-density wood types using the Thermo-Vibro-Mechanic® (TVM) densification process, a new and environmentally friendly modification method that provides an alternative to existing densification and modification processes. For this purpose, a special “TVM density press” was designed and produced with the support of Project No. 115O138 of the Scientific and Technological Research Council of Turkey (TUBITAK). The samples obtained as radial and tangential cross-sections from Uludağ fir (*Abies bornmüelleriana* Mattf.) and black poplar (*Populus nigra* L.) were pretreated with wood stain and wood preservative, and then these samples were subjected to the TVM densification process. Then, the resulting changes in the gloss and Brinell hardness values of the samples from the TVM densification process were determined.

EXPERIMENTAL

Materials

Uludağ fir (*Abies bornmüelleriana* Mattf.) and black poplar (*Populus nigra* L.), which are widely used in the forest products industry in Turkey, were preferred for the preparation of the samples. It was taken into consideration that the wood, procured in the

form of logs from the Forest Management in the Kütahya province of Turkey, would be robust with no growth defect or decay. The logs were cut into tangential and radial directions considering the dry weight and sample sizes, and transformed from fresh wood parts into rough-sized timbers with smooth fiber, without knots or cracks, and with no density or color differences (TS 2470 1976). These timbers were subjected to technical drying to achieve an air-dried moisture of 12%. Samples at air-dried moisture were cut at $360 \times 60 \times 21$ mm and $360 \times 110 \times 11$ mm size, and then sanded with 100-grit sandpaper *via* a calibrated sanding machine. Afterwards, they were impregnated with Akzo Nobel Kemipol brand-Unicolor Open Walnut (Catalog color-H 108 8001, AkzoNobel Kemipol AS, Kemalpaşa, Turkey) color aniline-based wood stain and Dewilux Dewitex 129-0174-52 brand colorless alkyd resin-based wood preservative (DYO Boya, İzmir, Turkey) prior to the TVM densification process using the 15 s dipping method. After the wood stain was mixed with 85% distilled water, the wood preservative was applied at the packaging viscosity. The samples were conditioned again at 20 ± 2 °C and $65 \pm 3\%$ relative humidity to eliminate the differences in humidity values occurring after these processes as per the TS 2471 standard (1976) (Fig. 1).



Fig. 1. Preparation of the samples

Methods

TVM densification process

The TVM densification process was conducted with constant linear vibration at 100 Hz frequency and 3 mm amplitude at three different temperatures (100 ± 3 °C, 120 ± 3 °C, and 140 ± 3 °C), three different vibration pressures (0.60 MPa, 1.00 MPa, and 1.40 MPa), and three different vibration times (20 s, 60 s, and 100 s). For this process, the samples placed on the TVM density press table specially designed and manufactured within the scope of the research were first kept under low pressure (2 kg/cm^2) so that both surfaces contacted with the press table, and they remained in this position until the internal temperature of the samples reached the target temperature values by checking with a digital thermometer (Fig. 2).

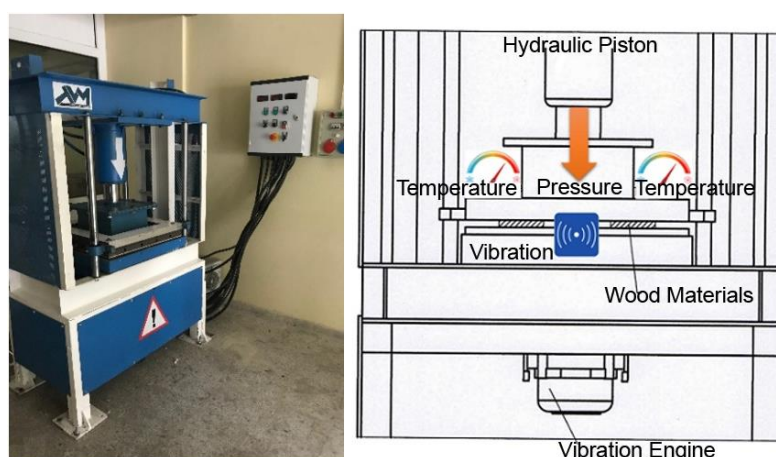


Fig. 2. TVM density press and working principle (Şenol 2018)

At the end of the TVM densification process, the samples were removed from the TVM density press and cooled to 60 °C at a different press (plating press) under 5 kg/cm² pressure to eliminate any spring-back effect (Fig. 3).



Fig. 3. Cooling the samples under pressure after TVM density operation

Then, the samples were kept in the climate chamber at 20 ± 2 °C temperature and $65 \pm 3\%$ relative humidity according to TS 2471 (1976) before trials until they reached a constant weight. Afterwards, the samples were sized to have 6 replications according to the TS 2479 (1976) and TS EN ISO 2813 (2014) standards of the tests to be applied.

Brinell hardness

The Brinell hardness values of the samples ($50 \times 20 \times 20$ mm) were determined using a UTEST 7012 (50 KN) test device according to TS 2479 (2016) principles (UTEST Material Testing Equipment, Ankara, Turkey). After a 10-mm diameter (D) half-sphere (steel ball) at the tip of the force application arm of the device was calibrated, so as to be at the center of the sample surface, the load was applied for 30 s. The load was reduced to zero in 15 s, and then the diameter of the pit that the steel ball opened on the sample surface was measured using a magnifying glass and a digital caliper with a precision of $(d) \pm 0.01$ mm (Fig. 4). The Brinell hardness value was calculated according to Eq. 1,

$$HB = \frac{2.F}{\pi.D(D - \sqrt{D^2 - d^2})} \quad (1)$$

where HB is the Brinell hardness value (N/mm²), F is the applied force (N), d is the diameter of the pit that the steel ball opened on the sample surface (mm), and D is the diameter of the steel ball (mm).

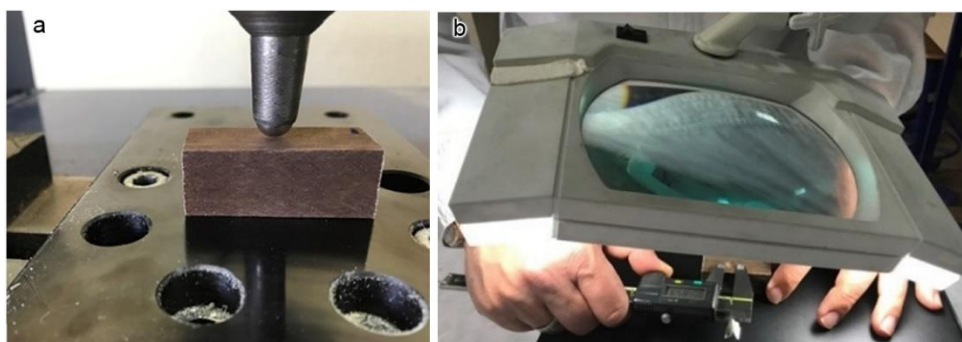


Fig. 4. Brinell hardness experiment (a) and measuring the pit diameter (b)

Gloss

Gloss measurements of the samples ($100 \times 100 \times 10$ mm) were determined using the BYK-Gardner Spectro-Guide 45/0 device (BYK-Gardner, Geretsried, Germany). The gloss measurements were made according to ISO 2813 (2014) using a 60 ° angle. After

TVM densification, measurements were made perpendicular and parallel to the fibers for each surface, and their arithmetic means were recorded as a single value (Fig. 5).



Fig. 5. Gloss measurement device

Scanning electron microscopy

To determine the effects of the wood type, sectional surface, surface process, and densification factors on the hardness and gloss performance, SEM images were taken of the cross-section (transverse) of wood materials. To obtain clearer images for this purpose, $4 \times 4 \times 4$ mm sized samples in groups of twelve were coated with gold metal using the Denton Vacuum Desk V (Denton, Moorestown, USA). The coated specimens were placed on the FEI Quanta FEG 250 SEM (FEI Company, Hillsboro, OR, USA) in such a way that measurements were taken from the section edge. Microscopic images were taken using the high-vacuum method.

Statistical analysis

An SPSS 22 statistical package program (IBM Corp., Armonk, NY, USA) was used to evaluate the data. Multivariate analysis of variance (ANOVA) tests determined the effects of wood type, sectional surface, surface process, densification factors, and the interactions of these factors on the hardness and gloss values at the 0.05 significance level. Comparisons were made using the Duncan's Multiple Range Test (DMRT) and least significant difference (LSD) critical values, and the factors causing the differences were examined.

RESULTS AND DISCUSSION

Brinell Hardness

The arithmetic means of the Brinell hardness values obtained to determine the effect of the TVM densification process on the Brinell hardness values of the samples were different according to wood type, section surface, surface process, and densification factors. An ANOVA was performed to determine which factor caused this difference, and the results are given in Table 1.

According to the results of the analysis of variance, wood type, sectional surface, surface process, and densification factors and the mutual interactions of these factors were significant ($p \leq 0.05$) with respect to the Brinell hardness values. Table 2 shows the DMRT comparison performed on the level of wood type, sectional surface, surface process, and densification factors using the LSD critical value.

Table 1. Results of ANOVA of Brinell Hardness Values

Factors	Degrees of Freedom	Sum of Squares	Mean Square	F Value	Level of Significance (p ≤ 0.05)
Wood Type (A)	1	20.146	20.146	8.602	0.0003*
Sectional Surface (B)	1	56.384	56.384	24.075	0.0000*
Surface Process (C)	2	577.796	288.898	123.356	0.0000*
Densification (D)	27	7320.014	271.112	115.761	0.0000*
Interaction (AB)	1	13.624	13.624	5.817	0.0016*
Interaction (AC)	2	90.634	45.317	19.350	0.0000*
Interaction (AD)	27	229.152	8.487	3.624	0.0000*
Interaction (BC)	2	72.168	36.084	15.407	0.0000*
Interaction (BD)	27	455.549	16.872	7.204	0.0000*
Interaction (CD)	54	478.931	8.869	3.787	0.0000*
Interaction (ABC)	2	82.396	41.198	17.591	0.0000*
Interaction (ABD)	27	112.591	4.170	1.781	0.0008*
Interaction (ACD)	54	271.311	5.024	2.145	0.0000*
Interaction (BCD)	54	355.641	6.586	2.812	0.0000*
Interaction (ABCD)	54	208.763	3.866	1.651	0.0002*
Error	1680	3934.535	2.342		
Total	2016	517448.021			

*Significant at 95% confidence level

According to Table 2, the Brinell hardness value was highest in the fir (15.9 N/mm²) and lowest in the poplar (15.7 N/mm²) at the wood type level; it was highest in the radial section (16.0 N/mm²) and lowest in the tangential section (15.6 N/mm²) at the sectional surface level; it was highest in the wood preservative applied samples (16.6 N/mm²) and lowest in the wood stain applied samples (15.4 N/mm²) at the surface process level; and it was highest in the samples where TVM densification was applied at 140 °C, 1.4 MPa, and 100 s (19.9 N/mm²), but lowest in samples without densification (control) (10.7 N/mm²) at the densification level.

At the wood type factor level, higher Brinell hardness values were obtained in the fir samples compared to the poplar samples. With the TVM densification process, high Brinell hardness was obtained in the fir (93.1%) and up to 82.8% in the poplar compared to the control samples. The high Brinell hardness value in the fir might have been caused by its coniferous structure and a noticeable difference between late wood and early wood. In the literature, it is emphasized that the content of late wood affects the hardness, abrasion, and resistance properties of wood (Kutnar and Šernek 2007; Lamason and Gong 2007; Rautkari *et al.* 2013; Şenol 2018).

According to the sectional surface factor, higher Brinell hardness values were obtained on the radial surface than the tangential surface. According to the TVM densification process, the Brinell hardness value was increased up to 100.9% on the radial surface and up to 77.8% on the tangential surface compared to the control. The high hardness values on the radial surface might have been due to the different reactions of the wood material to the radial and tangential compression because of its anisotropic structure, and the higher late wood rate in the radial section might have caused the porosity to decrease during densification. It is stated in the literature that densification mostly occurs in the lumens of early wood, so a possible cause of higher reaction of the samples with radial surface is that layers of both early wood and late wood have equal density during densification (Blomberg *et al.* 2005; Marttila *et al.* 2016), and the hardness values are higher in late wood compared to early wood because late wood is subjected to reinforcement (Rautkari *et al.* 2009).

Table 2. The DMRT Comparison Results for Wood Type, Section Surface, Surface Process, and Densification Factor (N/mm²)

Wood Type	\bar{x}	HG
Uludağ fir	15.898	A*
Black poplar	15.698	B
LSD \pm 0.048		
Sectional Surface	\bar{x}	HG
Radial	15.966	A*
Tangential	15.631	B
LSD \pm 0.048		
Surface Process	\bar{x}	HG
Natural	15.453	B
Wood stain	15.388	C
Wood preservative	16.555	A*
LSD \pm 0.059		
Densification	\bar{x}	HG
Control	10.66	P
100 °C - 0.6 MPa - 20 s	11.99	O
100 °C - 0.6 MPa - 60 s	13.23	N
100 °C - 0.6 MPa - 100 s	14.36	M
100 °C - 1.0 MPa - 20 s	14.84	LM
100 °C - 1.0 MPa - 60 s	15.73	HIJ
100 °C - 1.0 MPa - 100 s	16.31	FGH
100 °C - 1.4 MPa - 20 s	15.65	J
100 °C - 1.4 MPa - 60 s	16.86	E
100 °C - 1.4 MPa - 100 s	17.77	D
120 °C - 0.6 MPa - 20 s	14.74	LM
120 °C - 0.6 MPa - 60 s	15.77	HIJ
120 °C - 0.6 MPa - 100 s	15.90	GHIJ
120 °C - 1.0 MPa - 20 s	15.00	KL
120 °C - 1.0 MPa - 60 s	15.92	GHIJ
120 °C - 1.0 MPa - 100 s	16.25	FGHI
120 °C - 1.4 MPa - 20 s	16.00	GHIJ
120 °C - 1.4 MPa - 60 s	17.60	D
120 °C - 1.4 MPa - 100 s	19.58	B
140 °C - 0.6 MPa - 20 s	14.94	L
140 °C - 0.6 MPa - 60 s	15.48	JK
140 °C - 0.6 MPa - 100 s	16.37	EFG
140 °C - 1.0 MPa - 20 s	14.61	LM
140 °C - 1.0 MPa - 60 s	15.69	IJ
140 °C - 1.0 MPa - 100 s	16.74	EF
140 °C - 1.4 MPa - 20 s	16.25	FGHI
140 °C - 1.4 MPa - 60 s	18.28	C
140 °C - 1.4 MPa - 100 s	19.86	A*
LSD \pm 0.180		

\bar{x} : Arithmetic mean, HG: Homogeneity group, *: Highest Brinell hardness

Higher Brinell hardness values were obtained in the samples treated with wood preservative at the surface process factor level. After the TVM densification process, compared to the control (untreated), the following increases were obtained in Brinell hardness values: 110.7% in the samples treated with wood preservative, 97.5% in the natural (with no surface treatment) samples, and 89.9% in the wood stain samples. This was believed to be due to the oil alkyd, the main binder resin of the wood preservative. In the literature, it is emphasized that resin, the main characteristic element of varnish/paint, affects properties such as hardness, gloss, and adhesion (Sönmez and Budakçı 2001a,b; Budakçı and Sönmez 2005; Budakçı and Taşçıoğlu 2013; Budakçı and Pelit 2015).

According to the densification factor, it was found that depending on the parameters of the TVM densification process, the Brinell hardness values were increased by 62.6% to 150.5% compared to the control samples. This could have been explained by the increase in density of the wood material after the TVM densification process. In the literature, as a

result of the densification process, density increased due to the decrease of pore space in the wood material, the hardness values are closely related to the densification ratio, and the hardness values increase with the increasing densification ratio (Tabarsa and Chui 1997; Blomberg *et al.* 2005; Rautkari *et al.* 2009; Ünsal *et al.* 2011; Ulker *et al.* 2012; Ahmed *et al.* 2013; Pelit 2014; Marttila *et al.* 2016). The DMRT comparison results performed at the level of wood type, sectional surface, surface process, and densification factors interaction are shown in Fig. 6 to illustrate the results of single comparisons together.

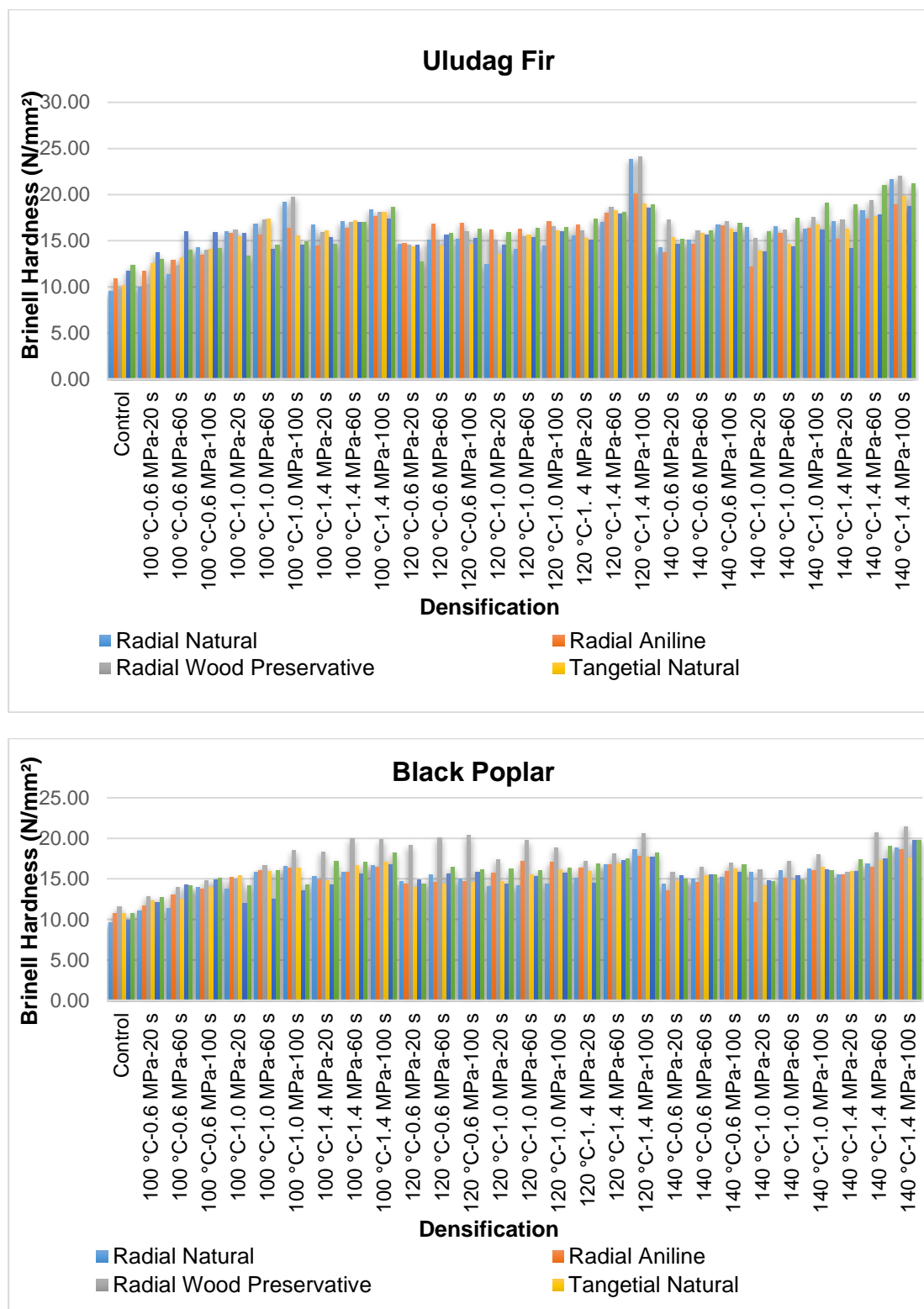


Fig. 6. The DMRT comparison results for Brinell hardness values at wood type, sectional surface, surface process, and densification interaction level

According to Fig. 6, the highest Brinell hardness value (24.08 N/mm²) was obtained in the wood preservative applied to fir samples with TVM densification on the radial section at 120 °C, 1.4 MPa, and 100 s. The lowest Brinell hardness value (9.51 N/mm²) was obtained in the untreated fir natural samples at the radial section without TVM densification. Brinell hardness values increased depending on the TVM densification process parameters, higher values were determined in higher compression ratios and long-term applications.

Gloss

The arithmetic means of the surface gloss values obtained to determine the effect of TVM densification on the surface gloss values of the samples were different according to the wood type, sectional surface, surface process, and densification factors. An ANOVA was performed to determine the factors causing this difference, and the results are given in Table 3.

Table 3. Results of Analysis of Variance Analysis of Surface Gloss Values

Factors	Degrees of Freedom	Sum of Squares	Mean Square	F Value	Level of Significance (p ≤ 0.05)
Wood Type (A)	1	816.684	816.684	2939.773	0.0000*
Sectional Surface	1	726.066	726.066	2613.579	0.0000*
Surface Process	2	18970.628	9485.314	34143.76	0.0000*
Densification (D)	27	10418.201	385.859	1388.956	0.0000*
Interaction (AB)	1	600.346	600.346	2161.031	0.0000*
Interaction (AC)	2	1715.698	857.849	3087.951	0.0000*
Interaction (AD)	27	511.998	18.963	68.260	0.0000*
Interaction (BC)	2	394.867	197.434	710.691	0.0000*
Interaction (BD)	27	314.59	11.651	41.941	0.0000*
Interaction (CD)	54	3032.161	56.151	202.124	0.0000*
Interaction (ABC)	2	37.127	18.563	66.821	0.0000*
Interaction (ABD)	27	279.366	10.347	37.245	0.0000*
Interaction (ACD)	54	777.775	14.403	51.847	0.0000*
Interaction (BCD)	54	509.937	9.443	33.992	0.0000*
Interaction (ABCD)	54	452.767	8.385	30.182	0.0000*
Error	1680	466.713	0.278		
Total	2016	233291.763			

*Significant at 95% confidence level

According to the results of analysis of variance, all factors and the mutual interactions of these factors were significant relative to the surface gloss values ($p \leq 0.05$). The results of the DMRT comparison performed at the level of wood type, sectional surface, surface process, and densification factors using the LSD critical value are given in Table 4.

According to Table 4, the surface gloss value was highest at the wood type level in the poplar (10.4) and lowest in the fir (9.2), the highest at the sectional surface level in tangential cross-section (10.4) and lowest in radial section (9.2), the highest at the surface process level in wood preservative applied samples (14.1) and lowest in wood stain applied samples (7.4), the highest in the TVM densification process applied samples at 140 °C, 1.4 MPa, and 100 s (13.3) as well as at 100 °C, 1.4 MPa, and 100 s (13.22); and the lowest in the control samples without densification process (2.70).

Higher gloss values were obtained in the poplar samples at the wood type factor level compared to the fir samples. After the TVM densification process, a high gloss increase was achieved in fir by up to 375% and in poplar by up to 418%. Obtaining a higher gloss value increase in the poplar samples might have enabled more densification and a smoother surface due to its coarse texture and large vessel structure. According to these

results, the decrease in the roughness values of the densified sample surfaces and the increase of light reflectivity after the TVM densification process increased the gloss values. It is stated in the literature that smooth and bright surfaces reflect the whole or a large part of the beam (Sönmez 1989; Gurau and Irle 2017). In addition, according to the SEM images obtained, crushing/bending occurred after the TVM densification process in the cell structures near the surface, and superposition (overlapping) occurred. It could be said that this reduced surface roughness and increased density improved the gloss and hardness values remarkably (Figs. 7 and 8).

Table 4. DMRT Comparison Results for Wood Type, Sectional Surface, Surface Process, and Densification Factors

Wood Type	\bar{x}	HG
Uludağ fir	9.155	B
Black poplar	10.428	A*
LSD \pm 0.017		
Sectional Surface	\bar{x}	HG
Radial	9.191	B
Tangential	10.391	A*
LSD \pm 0.017		
Surface Process	\bar{x}	HG
Natural	7.886	B
Wood stain	7.368	C
Wood preservative	14.119	A*
LSD \pm 0.020		
Densification	\bar{x}	HG
Control	2.70	R
100 °C - 0.6 MPa - 20 s	7.52	O
100 °C - 0.6 MPa - 60 s	9.39	J
100 °C - 0.6 MPa - 100 s	11.36	F
100 °C - 1.0 MPa - 20 s	8.07	N
100 °C - 1.0 MPa - 60 s	9.74	I
100 °C - 1.0 MPa - 100 s	11.83	D
100 °C - 1.4 MPa - 20 s	9.03	K
100 °C - 1.4 MPa - 60 s	11.21	FG
100 °C - 1.4 MPa - 100 s	13.22	A*
120 °C - 0.6 MPa - 20 s	7.37	OP
120 °C - 0.6 MPa - 60 s	9.66	I
120 °C - 0.6 MPa - 100 s	12.17	C
120 °C - 1.0 MPa - 20 s	7.98	N
120 °C - 1.0 MPa - 60 s	9.45	J
120 °C - 1.0 MPa - 100 s	11.96	D
120 °C - 1.4 MPa - 20 s	8.72	L
120 °C - 1.4 MPa - 60 s	10.50	H
120 °C - 1.4 MPa - 100 s	12.90	B
140 °C - 0.6 MPa - 20 s	7.31	P
140 °C - 0.6 MPa - 60 s	9.33	J
140 °C - 0.6 MPa - 100 s	11.56	E
140 °C - 1.0 MPa - 20 s	7.38	OP
140 °C - 1.0 MPa - 60 s	9.40	J
140 °C - 1.0 MPa - 100 s	11.60	E
140 °C - 1.4 MPa - 20 s	8.45	M
140 °C - 1.4 MPa - 60 s	11.07	G
140 °C - 1.4 MPa - 100 s	13.27	A*
LSD \pm 0.062		

\bar{x} : Arithmetic mean, HG: Homogeneity group, *: Highest gloss value

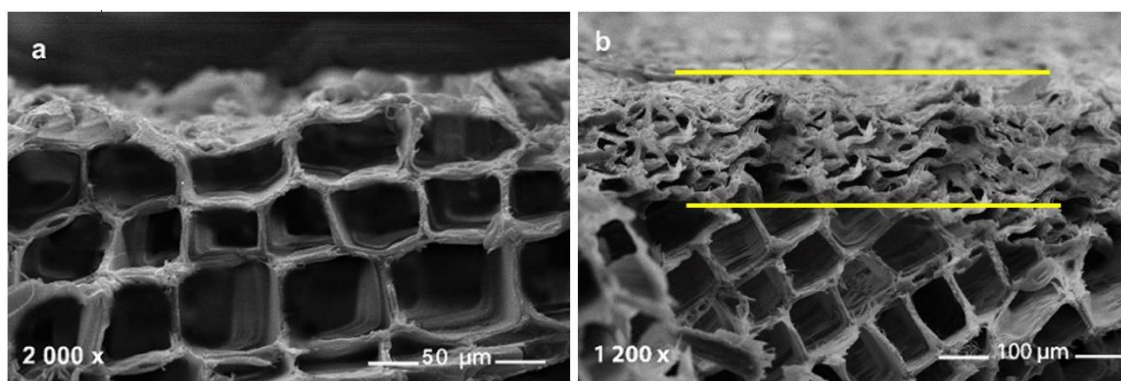


Fig. 7. SEM images of cross-sections of Uludağ fir wood samples: a) control (untreated) and b) after TVM process

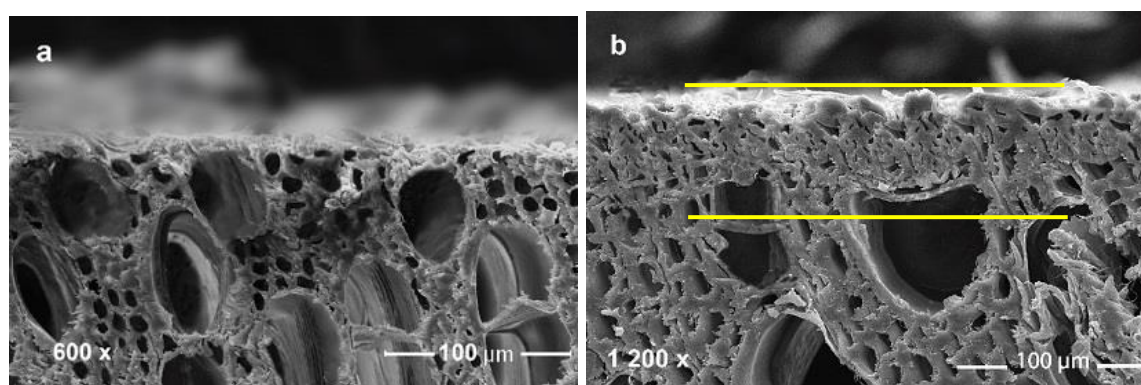


Fig. 8. SEM images of cross-sections of black poplar wood samples: a) control (untreated) and b) after TVM process

In this study, higher gloss values were obtained on tangential surfaces compared to radial surfaces at the level of the sectional surface factor. With the TVM densification process, the gloss increased by 372% on the radial surface and by 442% on the tangential surface compared to the control samples. In the literature, it is stated that the tangential section forms a smoother surface than the radial section (Sönmez *et al.* 2002; Budakçı *et al.* 2011; İlçe 2018). Thus, this study is compatible with the literature.

Higher gloss values were obtained in the wood preservative-applied samples at the surface process factor level. After the TVM densification process, compared to the control (untreated) samples, the following increases were obtained in the gloss values: 505% in wood preservative-applied samples, 220% in natural (with no surface treatment) samples, and 215% in the wood stain samples. Gloss values of the samples treated with the wood preservative were higher than the natural (with no surface treatment) and wood stain-treated samples. Alkyd resin and oily compounds in the wood preservative content were considered effective in this result. A similar situation was also found in the Brinell hardness values.

In terms of the densification factor, depending on the parameters of the TVM densification process, the gloss values were increased by 175% to 1390% compared to the control samples. It is reported in the literature that compared to the untreated surface, the surface densification of applied wood material shows a smooth surface, this application increases the gloss value 700%, and the results depend on surface densification process and process density (Rautkari *et al.* 2008; Rautkari 2012).

The DMRT comparison results performed at the level of wood type, sectional surface, surface process, and densification factors interaction are shown in Fig. 9 to show the results of the single comparisons together.

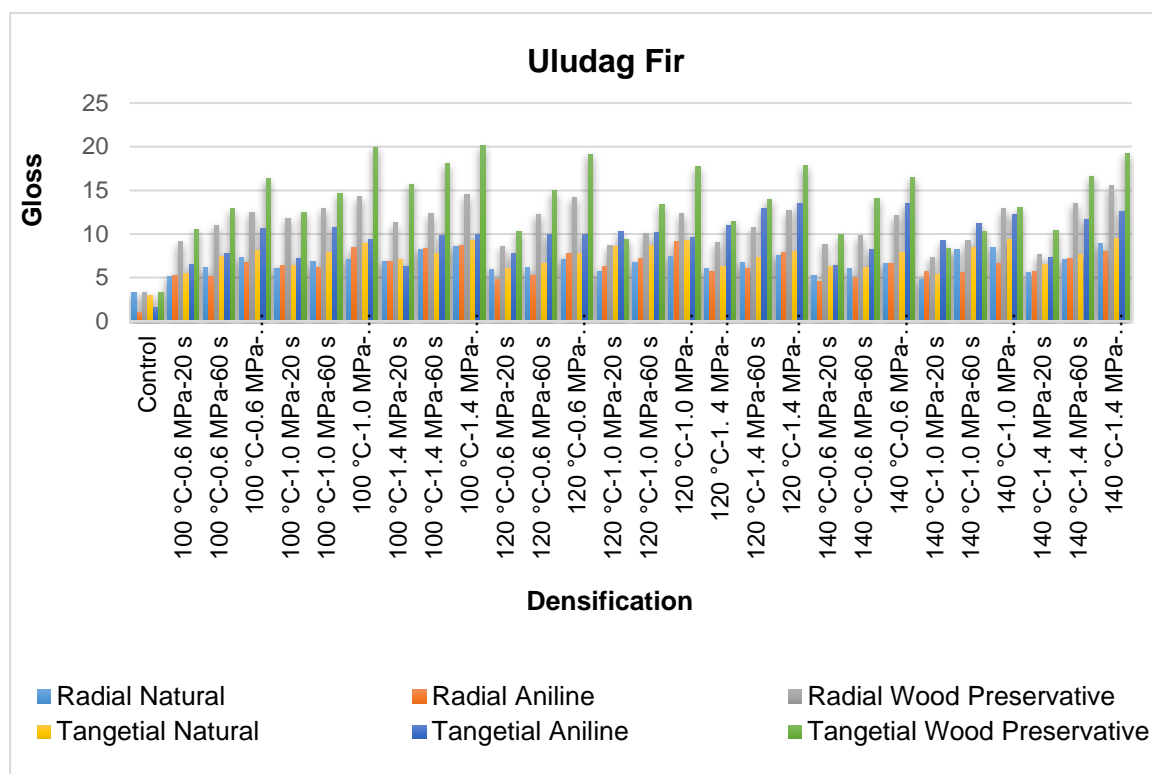


Fig. 9. The DMRT comparison results for gloss values at wood type, sectional surface, surface process, and densification interaction level

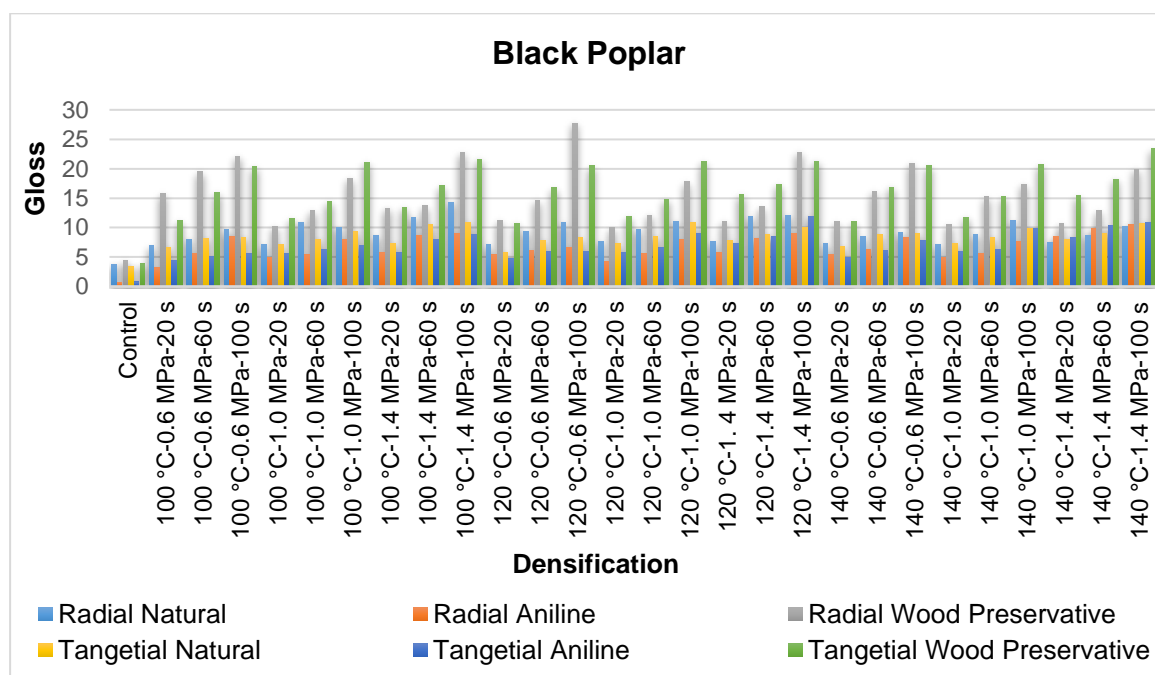


Fig. 9 (continued). The DMRT comparison results for gloss values at wood type, sectional surface, surface process, and densification interaction level

According to the results of Fig. 9, the highest gloss value obtained was in the wood preservative-treated poplar samples (27.73) in the radial section with TVM densification at 120 °C, 0.6 MPa, and 100 s. The lowest gloss value was obtained in the wood stained poplar control samples (0.72) in the radial section without TVM densification and in the wood stained poplar control samples (0.80) in the tangential section without TVM densification.

It was thought that the surface gloss values increased depending on the parameters of the TVM densification process as well as the effect of the wood preservative that formed a layer on the surface, which increased the gloss value. In the literature, it is stated that the high gloss value shows a smooth surface and therefore the densified surface is probably very smooth (Rautkari *et al.* 2008). In addition, it has been reported in other studies that the densification process reduces the surface roughness considerably (Arruda and Del Menezzi 2013), and that the densified wood material may have a smooth and bright surface without using any surface coating (Lamason and Gong 2007).

CONCLUSIONS

1. This study aimed to develop an innovative new method called Thermo-Vibro-Mechanic[®] densification as an alternative to densification and thermal modification processes and to obtain wood material with high performance by improving the resistance characteristics of low-density wood types. For this purpose, samples obtained as radial and tangential sections from the Uludağ fir (*Abies bornmülleriana* Mattf.) and black poplar (*Populus nigra* L.) were treated with wood stain (aniline) and a colorless oily wood preservative coating prior to the TVM densification process.
2. The study determined that the TVM densification process would be a new and environmentally friendly alternative method to other wood modification methods. The Brinell hardness and gloss values of Uludağ fir and black poplar woods with low resistance characteristics were improved with the TVM densification process.
3. In accordance with the data obtained, a noticeable increase in the surface smoothness was observed after TVM densification operation, and consequently significant increases were determined in the gloss values. According to these results, the positive results of TVM for the performance of the paint and varnish layers (adhesion, hardness, gloss, smoothness, *etc.*) to be applied to the surface of the wood material could be counted among the important results of the study. Removal of the sanding operation after the TVM densification process would allow for decreased labor, saving time, and is more economical.
4. Significant increases were observed in the Brinell hardness values depending on the densification level after the TVM densification process. The limited use of the relatively low-density wood types in the world could be extended by improving the resistance characteristics of this species using this method.
5. The highest Brinell hardness and gloss values were obtained in the samples to which TVM densification was applied at high temperature (140 °C), high pressure (1.4 MPa), and long duration (100 s). It could be recommended to prefer alternative parameters for the Brinell hardness values, such as 140 °C, 1.4 MPa, and 100 s, for gloss values like 120 °C, 0.6 MPa, and 100 s, or to do additional studies by using different densification parameters to enhance the mechanical properties.

ACKNOWLEDGMENTS

This research has been written in memory of Dr. Süleyman Şenol, who passed away on May 10, 2019. The study was supported by Project No. 115O138 within the scope of the “TÜBİTAK-3001 Start R&D Projects Support Program”. In addition, Thermo-Vibro-Mechanic[®] (TVM) the trademark was registered on July 01, 2019 with Number: 2018/120796 by the Turkish Patent and Trademark Authority. Also, Thermo-Vibro-

Mechanic® (TVM) density press patent registration process has been continued with Application Number. 2019/01054.

REFERENCES CITED

- Ahmed, S. A., Morén, T., Hagman, O., Cloutier, A., Fang, C.-H., and Elustondo, D. (2013). "Anatomical properties and process parameters affecting blister/blow formation in densified European aspen and downy birch sapwood boards by thermo-hygro-mechanical compression," *J. Mater. Sci.* 48(24), 8571-8579. DOI: 10.1007/s10853-013-7679-9
- Arruda, L. M., and Del Menezzi, C. H. S. (2013). "Effect of thermomechanical treatment on physical properties of wood veneers," *Int. Wood Prod. J.* 4(4), 217-224. DOI: 10.1179/2042645312Y.0000000022
- Bekhta, P., and Niemz, P. (2003). "Effect of high temperature on the change in color, dimensional stability and mechanical properties of spruce wood," *Holzforschung* 57(5), 539-546. DOI: 10.1515/HF.2003.080
- Blomberg, J., and Persson, B. (2004). "Plastic deformation in small clear pieces of Scots pine (*Pinus sylvestris*) during densification with the CaLignum process," *J. Wood Sci.* 50(4), 307-314. DOI: 10.1007/s10086-003-0566-2
- Blomberg, J., Persson, B., and Bexell, U. (2006). "Effects of semi-isostatic densification on anatomy and cell-shape recovery on soaking," *Holzforschung* 60(3), 322-331. DOI: 10.1515/HF.2006.052
- Blomberg, J., Persson, B., and Blomberg, A. (2005). "Effects of semi-isostatic densification of wood on the variation in strength properties with density," *Wood Sci. Technol.* 39(5), 339-350. DOI: 10.1007/s00226-005-0290-8
- Boonstra, M. (2008). *A Two-Stage Thermal Modification of Wood*, Ph.D. Dissertation, Ghent University and Université Henry Poincaré, Nancy, France. DOI: 1854/10505
- Budakçı, M., İlçe, A. C., Korkut, D. S., and Gürleyen, T. (2011). "Evaluating the surface roughness of heat-treated wood cut with different circular saws," *BioResources* 6(4), 4247-4258. DOI: 10.15376/biores.6.4.4247-4258
- Budakçı, M., and Pelit, H. (2015). "Effect of the oil based wood protective on adhesion strength of polyester varnish," *Selcuk-Technic Journal, Special Edition (UMK-2015)* 1, 886-895.
- Budakçı, M., Pelit, H., Sönmez, A., and Korkmaz, M. (2016). "The effects of densification and heat post-treatment on hardness and morphological properties of wood materials," *BioResources* 11(3), 7822-7838. DOI: 10.15376/biores.11.3.7822-7838
- Budakçı, M., and Sönmez, A. (2005). "The effects of drying time to wood protectors on adhesion strength of varnish coatings," in: *1st International Vocational and Technical Education Technologies Congress*, İstanbul, Turkey, pp. 1486-1494.
- Budakçı, M., and Taşçıoğlu, C. (2013). "Adhesion properties of some protective layers exposed to outside weather conditions for five years," *Turk. J. Agric. For.* 37, 126-132. DOI: 10.3906/tar-1202-24
- Esteves, B., Marques, A. V., Domingos, I., and Pereira, H. (2007). "Influence of steam heating on the properties of pine (*Pinus pinaster*) and eucalypt (*Eucalyptus globulus*) wood," *Wood Sci. Technol.* 41, 193-207. DOI: 10.1007/s00226-006-0099-0
- Fang, C. H., Mariotti, N., Cloutier, A., Koubaa, A., and Blanchet, P. (2012). "Densification of wood veneers by compression combined with heat and steam," *Eur. J. Wood Wood Prod.* 70(1-3), 155-163. DOI: 10.1007/s00107-011-0524-4

- Fu, Q., Cloutier, A., and Laghdir, A. (2017). "Effect of heat and steam on the mechanical properties and dimensional stability of thermos-hygromechanically densified sugar maple wood," *BioResources* 12(4): 9212-9226. DOI: 10.15376/biores.12.4.9212-9226
- Gaff, M., and Gašparík, M. (2013). "Shrinkage and stability of thermo-mechanically modified aspen wood," *BioResources* 8(1), 1136-1146. DOI: 10.15376/biores.8.1.1136-1146
- Gao, Z., Huang, R., Chang, J., Li, R., and Wu, Y. (2019). "Effects of pressurized superheated-steam heat treatment on set recovery and mechanical properties of surface-compressed wood," *BioResources* 14(1), 1718-1730. DOI: 10.15376/biores.14.1.1718-1730
- Gong, M., and Lamason, C. (2007). *Improvement of Surface Properties of Low Density Wood: Mechanical Modification with Heat Treatment* (Project No. UNB57), University of New Brunswick, Fredericton, Canada.
- Gurau, L., and Irle, M. (2017). "Surface roughness evaluation methods for wood products: A review," *Current Forestry Reports* 3(2), 119-131. DOI: 10.1007/s40725-017-0053-4
- İlçe, A. (2018). "Determination of surface roughness based on the sanding parameters of oriental beech wood," *BioResources* 13(3), 5942-5952. DOI: 10.15376/biores.13.3.5942-5952
- ISO 2813 (2014). "Paints and varnishes - Determination of gloss value at 20 degrees, 60 degrees and 85 degrees," International Organization for Standardization, Geneva, Switzerland.
- Kamke, F. A. (2006). "Densified radiata pine for structural composites," *Maderas- Cienc. Tecnol.* 8(2), 83-92. DOI: 10.4067/S0718-221X2006000200002
- Kollmann, F. F., Kuenzi, E. W., and Stamm, A. J. (1975). *Principles of Wood Science and Technology II. Wood Based Materials*, Springer - Verlag, Berlin, Germany.
- Korkut, S., and Kocaefe, D. (2009). "Effect of heat treatment on wood properties," *Düzce University Journal of Forestry* 5(2), 11-34.
- Kultikova, E. V. (1999). *Structure and Properties Relationships of Densified Wood*, Master's Thesis, Virginia Polytechnic Institute and State University, Blacksburg, VA, USA.
- Kutnar, A., Kamke, F. A., and Sernek, M. (2009). "Density profile and morphology of viscoelastic thermal compressed wood," *Wood Sci. Technol.* 43(1-2), 57-68. DOI: 10.1007/s00226-008-0198-1
- Kutnar, A., and Šernek, M. (2007). "Densification of wood," *Zbornik Gozdarstva in Lesarstva* 82, 53-62.
- Lamason, C., and Gong, M. (2007). "Optimization of pressing parameters for mechanically surface-densified aspen," *Forest Prod. J.* 57(10), 64-68.
- Laine, K., Segerholm, K., Wålinder, M., Rautkari, L., Ormondroyd, G., Hughes, M., and Jones, D. (2014). "Micromorphological studies of surface densified wood," *J. Mater. Sci.* 49(5), 2027-2034. DOI: 10.1007/s10853-013-7980-8
- Li, T., Cai, J., Avramidis, S., Cheng, D., Wålinder, M. E. P., and Zhou, D. (2017). "Effect of conditioning history on the characterization of hardness of thermo-mechanical densified and heat treated poplar wood," *Holzforschung* 71(6), 515-520. DOI: 10.1515/hf-2016-0178
- Marttila, J., Möttönen, V., Bütün, Y., and Heräjärvi, H. (2016). "Bending properties of tangentially and radially sawn European aspen and silver birch wood after industrial scale thermo-mechanical modification," in: *2nd Conference on Engineered Wood Products based on Poplar/willow Wood*, León, Spain, pp. 113-124.
- Morsing, N., and Hoffmeyer, P. (1998). *Densification of Wood - The Influence of Hygrothermal Treatment on Compression of Beech Perpendicular to Grain*, Ph.D. Dissertation, Technical University of Denmark, Kongens Lyngby, Denmark.

- Pelit, H. (2014). *The Effects of Densification and Heat Treatment on Finishing Process with Some Technological Properties of Eastern Beech and Scots Pine*, Ph.D. Dissertation, Gazi University, Ankara, Turkey.
- Pelit, H., Budakçı, M., and Sönmez, A. (2018). "Density and some mechanical properties of densified and heat post-treated Uludağ fir, linden and black poplar woods," *Eur. J. Wood Wood Prod.* 76(1), 79-87. DOI: 10.1007/s00107-017-1182-y
- Pelit, H., Sönmez, A., and Budakçı, M. (2014). "Effects of ThermoWood® process combined with thermo-mechanical densification on some physical properties of Scots pine (*Pinus sylvestris* L.)," *BioResources* 9(3), 4552-4567. DOI: 10.15376/biores.9.3.4552-4567
- Pelit, H., Sönmez, A., and Budakçı, M. (2015). "Effects of thermomechanical densification and heat treatment on density and Brinell hardness of Scots pine (*Pinus sylvestris* L.) and Eastern beech (*Fagus orientalis* L.)." *BioResources* 10(2), 3097-3111. DOI: 10.15376/biores.10.2.3097-3111
- Rautkari, L. (2012). *Surface Modification of Solid Wood Using Different Techniques*, Ph.D. Dissertation, Aalto University, Espoo, Finland.
- Rautkari, L., Kamke, F. A., and Hughes, M. (2011). "Density profile relation to hardness of viscoelastic thermal compressed (VTC) wood composite," *Wood Sci. Technol.* 45(4), 693-705. DOI: 10.1007/s00226-010-0400-0
- Rautkari, L., Laine, K., Kutnar, A., Medved, S., and Hughes, M. (2013). "Hardness and density profile of surface densified and thermally modified Scots pine in relation to degree of densification," *J. Mater. Sci.* 48(6), 2370-2375. DOI: 10.1007/s10853-012-7019-5
- Rautkari, L., Properzi, M., Pichelin, F., and Hughes, M. (2008). "An innovative thermo densification method for wooden surfaces," in: *Proceedings of the 10th World Conference on Timber Engineering*, Miyazaki, Japan.
- Rautkari, L., Properzi, M., Pichelin, F., and Hughes, M. (2009). "Surface modification of wood using friction," *Wood Sci. Technol.* 43(3-4), 291-299. DOI: 10.1007/s00226-008-0227-0
- Rautkari, L., Properzi, M., Pichelin, F., and Hughes, M. (2010). "Properties and set-recovery of surface densified Norway spruce and European beech," *Wood Sci. Technol.* 44(4), 679-691. DOI: 10.1007/s00226-009-0291-0
- Sandberg, D., Kutnar, A., and Mantanis, G. (2017). "Wood modification technologies - A review," *Forest Biogeosciences and Forestry* 10(6), 895-908. DOI: 10.3832/for2380-010
- Seborg, R. M., Millett, M. A., and Stamm, A. J. (1956). *Heat-stabilized Compressed Wood* (Staypak) (Report No. 1580), U.S. Department of Agriculture Forest Products Laboratory, Madison, WI, USA.
- Song, J., Chen, C., Zhu, S., Zhu, M., Dai, J., Ray, U., Li, Y., Kuang, Y., Li, Y., Quispe, N., Yao, Y., Gong, A., Leiste U. H., Bruck, H. A., Zhu, J. Y., Vellore, A., Li, H., Minus, M. L., Jia, Z., Martini, A., Li, T., and Hu, L. (2018). "Processing bulk natural wood into a high-performance structural material," *Nature* 554(7691), 224. DOI:10.1038/nature25476
- Sönmez, A. (1989). *Durability of Varnishes Used on Surfaces of Wood Furniture Against Important Physical, Mechanical, and Chemical Effects*, Ph.D. Dissertation, Gazi University, Ankara, Turkey.
- Sönmez, A., and Budakçı, M. (2001a). "The effect of wood protective of the adhesion resistance of outer usage varnish coatings," *Gazi Univ. J. Sci.* 14(2), 305-314.
- Sönmez, A., and Budakçı, M. (2001b). "The effect of outdoor condition on the outer usage varnishes," *Gazi Univ. J. Sci.* 14(3), 697-708.

- Sönmez, A., Budakçı, M., and Gürleyen, L. (2002). "The effect of surface smoothness on bonding strength for ACACİA wood that processed with knives planer (HSS)," *The Journal of the Industrial Arts Education Faculty of Gazi University* 9(9), 29-40.
- Şenol, S. (2018). *Determination of Physical, Mechanical and Technological Properties of Some Wood Materials Treated with Thermo-Vibro-Mechanical (TVM) Process*, Ph.D. Thesis, Düzce University, Düzce, Turkey.
- Şenol, S., and Budakçı, M. (2016). "Mechanical wood modification methods," *Mugla Journal of Science and Technology* 2(2), 53-59.
- Şenol, S., and Budakçı, M. (2018). "The effect of thermo-vibro-mechanical (TVM) densification method on the density and abrasion resistance of pre-treated some wood materials," in: *Proceedings of the 5th International Furniture and Decoration Congress*, Eskişehir, Turkey, pp. 481-492.
- Şenol, S., Budakçı, M., and Korkmaz, M. (2017). "The effect of thermo-vibro-mechanical (TVM) densification process on density and abrasion resistance of some wood materials," in: *Proceedings of the 4th International Furniture and Decoration Congress*, Düzce, Turkey, pp. 322-334.
- Tabarsa, T., and Chui, Y. H. (1997). "Effects of hot-pressing on properties of white spruce," *Forest Prod. J.* 47(5), 71-76.
- TS 2470 (1976). "Wood - Sampling methods and general requirements for physical and mechanical tests," Turkish Standards Institution, Ankara, Turkey.
- TS 2471 (1976). "Wood - Determination of moisture content for physical and mechanical tests," Turkish Standards Institution, Ankara, Turkey.
- TS 2479 (1976). "Wood - Determination of static hardness," Turkish Standards Institution, Ankara, Turkey.
- Ünsal, O., Candan, Z., Büyüksarı, Ü., Korkut, S., Chang, Y.-S., and Yeo, H.-M. (2011). "Effect of thermal compression treatment on the surface hardness, vertical density propile and thickness swelling of eucalyptus wood boards by hot-pressing," *J. Korean Wood Sci. Technol.* 39(2), 148-155. DOI: 10.5658/WOOD.2011.39.2.148
- Ulker, O., Imirzi, O., and Burdurlu, E. (2012). "The effect of densification temperature on some physical and mechanical properties of Scots pine (*Pinus sylvestris* L.)," *BioResources* 7(4), 5581-5592. DOI: 10.15376/biores.7.4.5581-5592

Article submitted: May 15, 2019; Peer review completed: October 1, 2019; Revised version received: October 11, 2019; Accepted: October 12, 2019; Published: October 21, 2019.

DOI: 10.15376/biores.14.4.9611-9627

Copyright of BioResources is the property of North Carolina State University c/o Forest Biomaterials and its content may not be copied or emailed to multiple sites or posted to a listserv without the copyright holder's express written permission. However, users may print, download, or email articles for individual use.