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

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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;

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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

Uludag 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 × 60 × 21 mm and 360 × 110 × 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 ± 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).

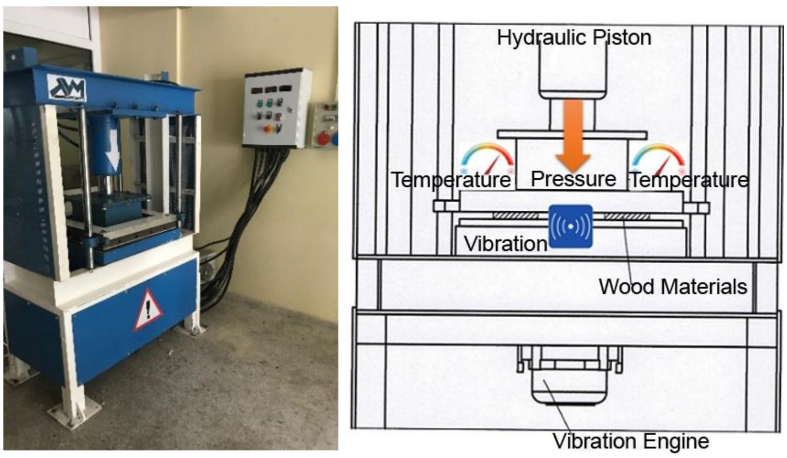


Fig. 2. TVM density press and working principle (Şenol 2018)

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/cm^2 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 ± 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 × 20 × 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) ± 0.01 mm (Fig. 4). The Brinell hardness value was calculated according to Eq. 1,

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

where *HB* is the Brinell hardness value (N/mm^2), *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).

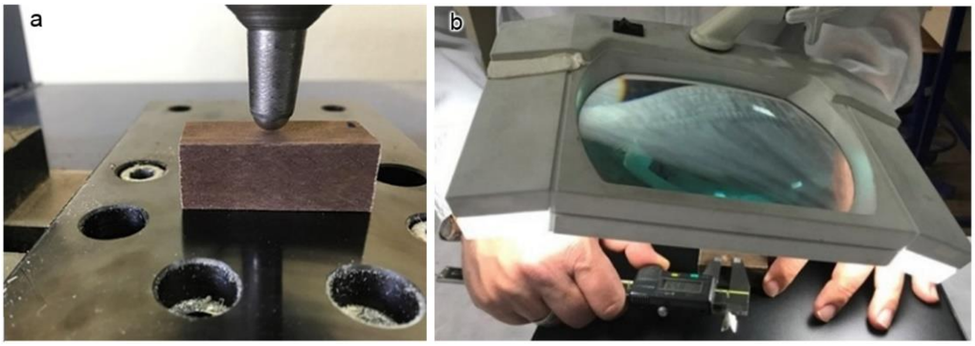


Fig. 4. Brinell hardness experiment (a) and measuring the pit diameter (b)

Gloss

Gloss measurements of the samples (100 × 100 × 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 × 4 × 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 ($p \leq 0.05$)
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/mm^2) and lowest in the poplar (15.7 N/mm^2) at the wood type level; it was highest in the radial section (16.0 N/mm^2) and lowest in the tangential section (15.6 N/mm^2) at the sectional surface level; it was highest in the wood preservative applied samples (16.6 N/mm^2) and lowest in the wood stain applied samples (15.4 N/mm^2) 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/mm^2), but lowest in samples without densification (control) (10.7 N/mm^2) 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).

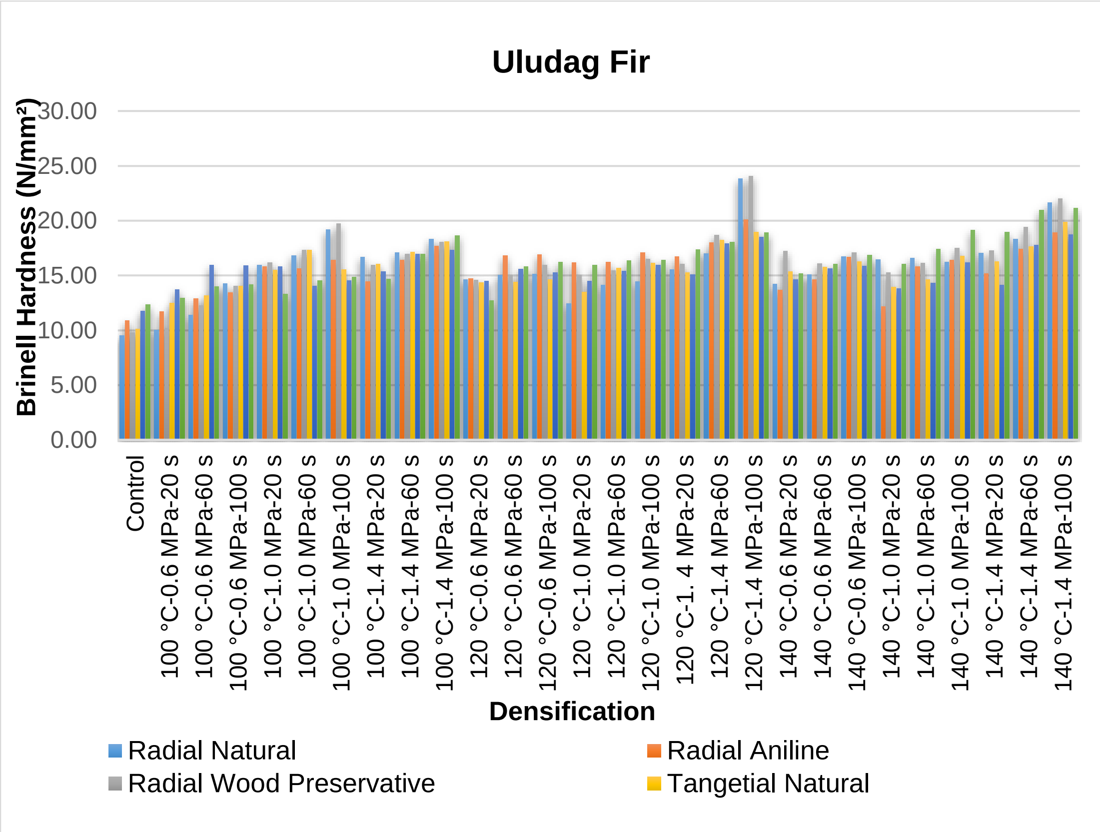
Table 2. The DMRT Comparison Results for Wood Type, Section Surface, Surface Process, and Densification Factor (N/mm^2)

Wood Type	$\bar{x}$	**HG**
Uludağ fir	15.898	A*
Black poplar	15.698	B
LSD ± 0.048		
Sectional Surface	$\bar{x}$	**HG**
Radial	15.966	A*
Tangential	15.631	B
LSD ± 0.048		
Surface Process	$\bar{x}$	**HG**
Natural	15.453	B
Wood stain	15.388	C
Wood preservative	16.555	A*
LSD ± 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 ± 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.



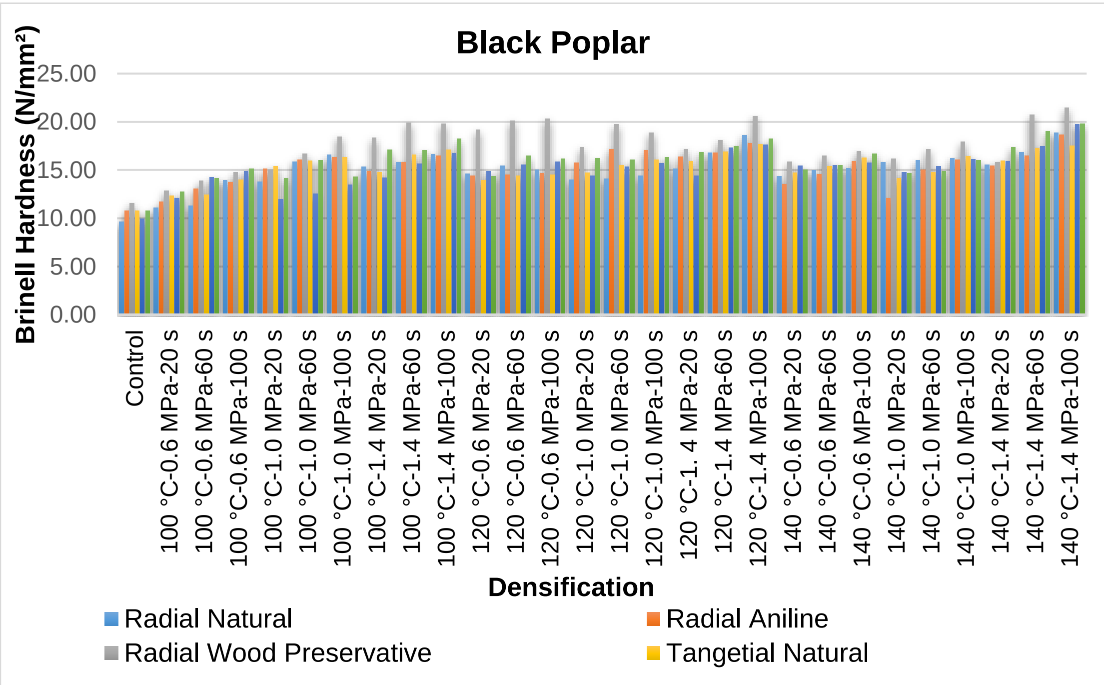


Fig. 6. The DMRT comparison results for Brinell hardness values at wood type, sectional surface, surface process, and densification interaction level

According to Fig. 6, the highest Brinell hardness value (24.08 N/mm^2) 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/mm^2) 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 ± 0.017		
Sectional Surface	$\bar{x}$	**HG**
Radial	9.191	B
Tangential	10.391	A*
LSD ± 0.017		
Surface Process	$\bar{x}$	**HG**
Natural	7.886	B
Wood stain	7.368	C
Wood preservative	14.119	A*
LSD ± 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 ± 0.062		

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

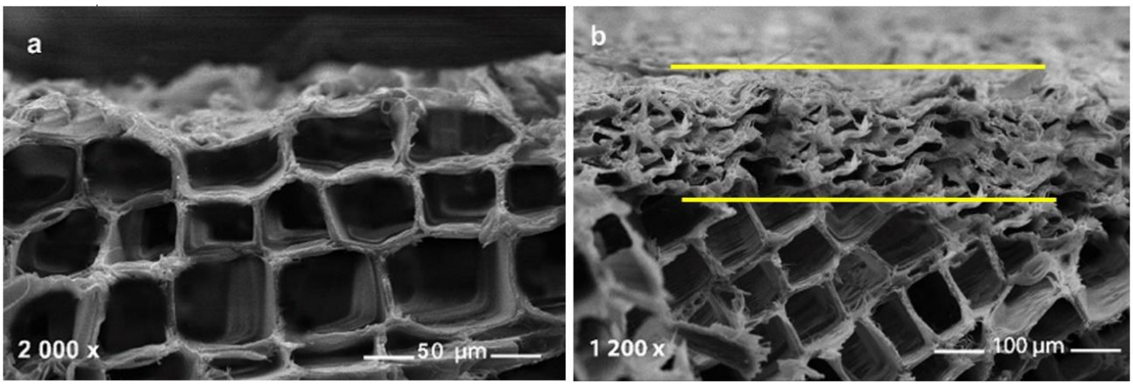


Fig. 7. SEM images of cross-sections of Uludağ fir wood samples: a) control (untreated) and b) after TVM process

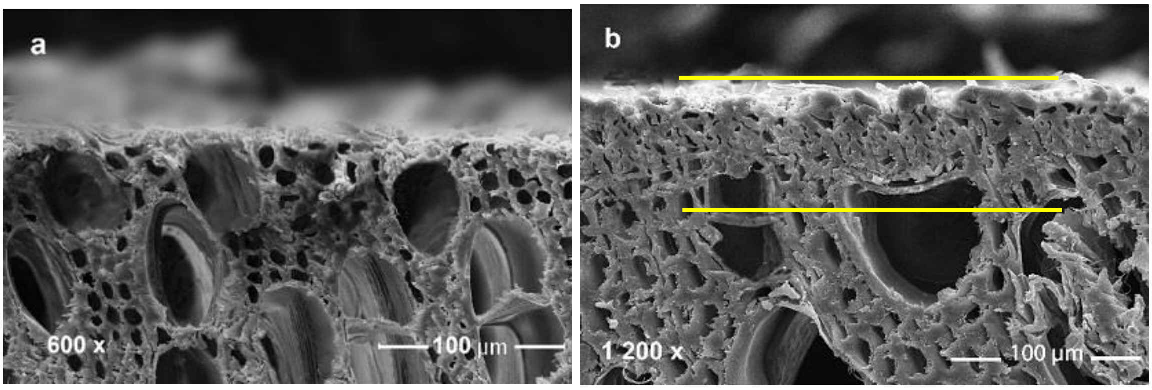


Fig. 8. SEM images of cross-sections of black poplar wood samples: a) control (untreated) and b) after TVM process

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.

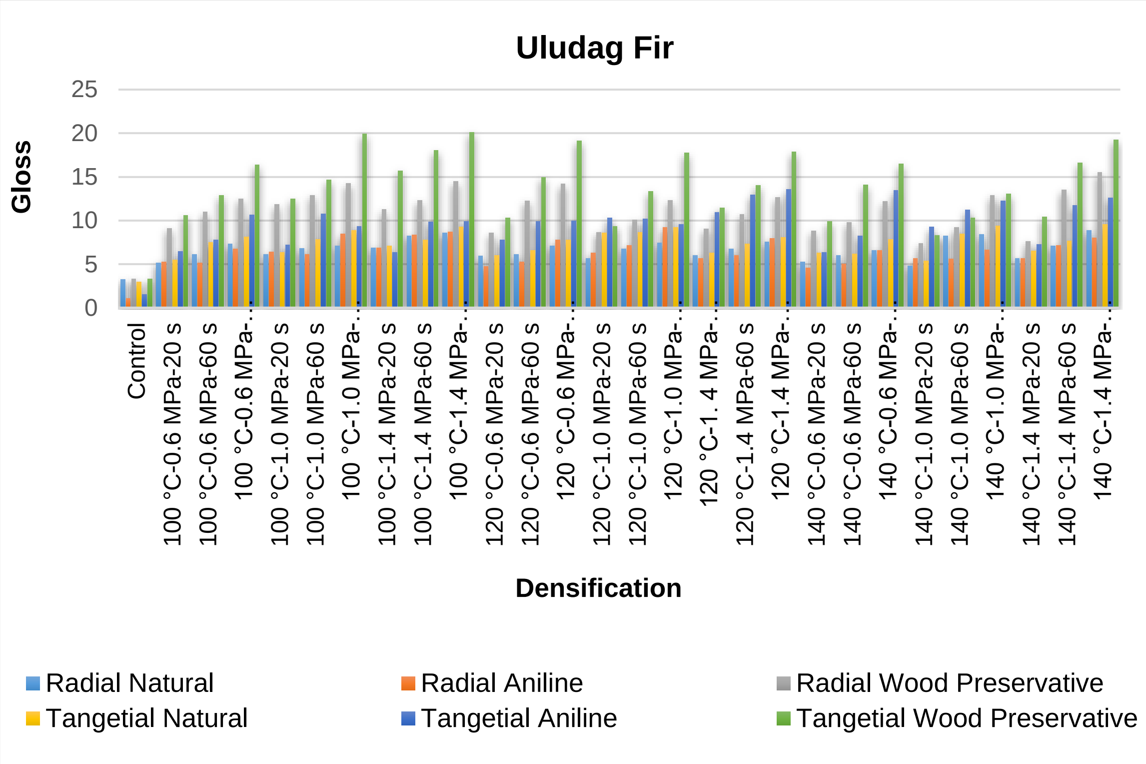


Fig. 9. The DMRT comparison results for gloss values at wood type, sectional surface, surface process, and densification interaction level

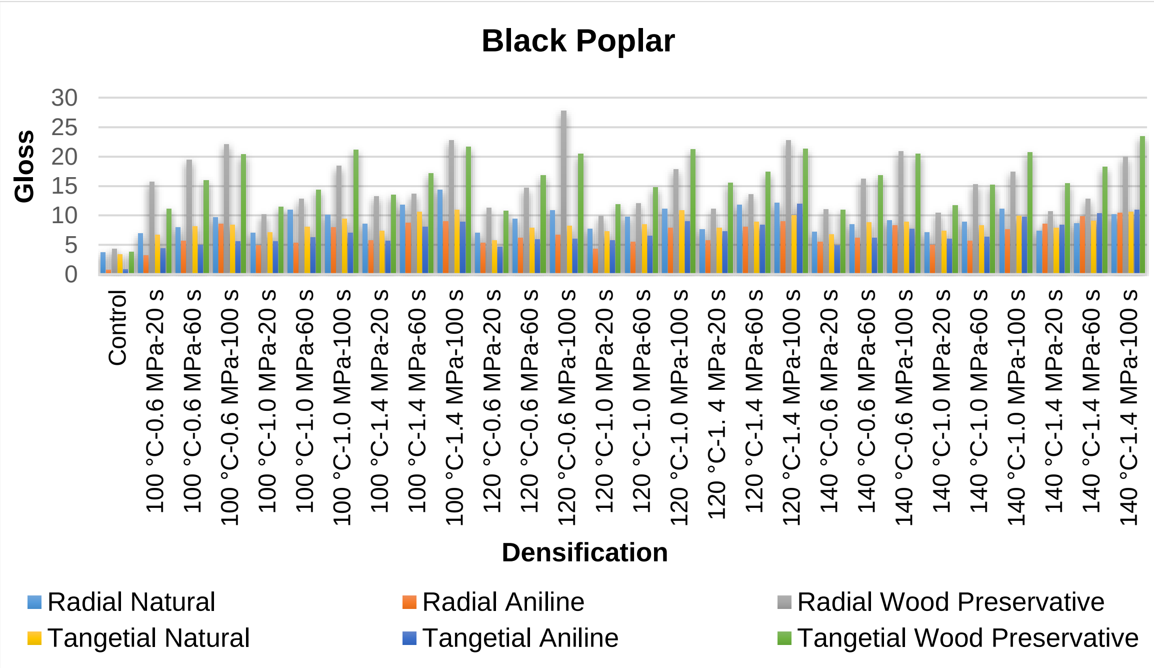


Fig. 9 (continued). The DMRT comparison results for gloss values at wood type, sectional surface, surface process, and densification interaction level

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 bornmüelleriana* 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.

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

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