Thermo-Vibro-Mechanic® (TVM) Wood Densification Method: Mechanical Properties

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A densification method is proposed and developed to improve the mechanical properties of Uludağ fir *(Abies bornmüelleriana* Mattf.*)* and black poplar (*Populus nigra* L.) woods. The method, called Thermo-Vibro-Mechanic® densification, is derived from the hypothesis that the vibration added to the traditional thermo-mechanical densification process can cause the wood cell walls to interlock with each other at the micro-level *via* the friction effect. In addition, it aims to remove the cell cavities under lower pressure compared to other densification methods *via* the shaking effect. To test this hypothesis, the samples, obtained in both the radial and tangential directions, were pre-treated with wood stain and preservative before undergoing the densification process. Thermo-Vibro-Mechanic® densification was performed at varying temperatures (100, 120, and 140 °C), pressures (0.60, 1.00, and 1.40 MPa), and durations (20, 60, and 100 s). The changes in the values of the bending strength, modulus of elasticity, and compression strength parallel to the grain in the radial and tangential directions were determined accordingly. The results showed that the Thermo-Vibro-Mechanic® densification process increased the bending strength and modulus of elasticity values up to 50%, while the compression strength reached 67% higher than the untreated wood.

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INTRODUCTION

The use of wood materials in different areas and for different purposes is becoming popular with the developments in woodworking technology. Thanks to wood modification methods, certain wood can be used even in processes where its use was not possible until a few decades ago. Wood modification, which is defined as changing the structure of the wood material while applying new features, is a general term used for chemical, mechanical, thermal, *etc.* processes applied to wood. It includes many methods *e.g.*, heat treatment, impregnation, densification, and surface modification (Hill 2006; Boonstra 2008; Petrič 2013).

According to a database containing more than 16,000 tree species spread around the world, the average global wood density is approximately 0.61 g/cm^3 (Zanne *et al.* 2009). Wood shows very high resistance against static and dynamic loads, although the wood material typically is lighter in comparison to many building materials. Wood materials, which have a very high specific resistance (strength-to-weight ratio) compared to other materials, often provide better results than titanium or steel in terms of the specific tensile strength (Stalnaker and Harris 1989; Boyer *et al.* 1994).

Density is one of the most important parameters of a wood material, as it has a direct effect on its strength and durability (Evans and Ilic 2001; Downes *et al.* 2002; Blomberg *et al.* 2005; Kamke 2006; Kutnar and Sernek 2007). Therefore, dense wood types are preferred in industrial applications that require high strength. In general, fast-growing species tend to have a lower density than slow-growing ones (Udayakumar and Sekar 2017). Although slow-growing species show better mechanical properties, their commercial production requires a longer time (Black *et al.* 2008). However, many studies are carried out on the usage of timber obtained from low density and fast-growing tree species on an industrial scale (Wu *et al.* 2010; Han *et al.* 2015; Dong *et al.* 2016). The densification process, which is a mechanical modification method, is the frequently preferred method for increasing the density of low-density wood materials (Blomberg and Persson 2004; Blomberg *et al.* 2005; Kutnar and Sernek 2007; Pelit *et al.* 2015; Şenol and Budakçı 2016). In this regard, densification not only enables commercial use of fast-growing low-density trees, but it also contributes to the sustainability of slow-growing high-density species.

The amount of densification to be applied to the wood material is determined by the type of wood, as well as where and for what purpose the product will be used for (Kutnar and Sernek 2007). The density and strength properties of a densified wood vary according to the densification parameters, *e.g.*, temperature, softening and plasticizing period, and pressure. The proper selection of these parameters ensures a product with up to 2 times the density compared to the undensified one (Ülker *et al.* 2012; Ulker and Hiziroglu 2017; Gao *et al.* 2019).

A wood material without any modification has a sponge-like structure (Kollmann and Côté 1968). During the densification process, thanks to this porous structure, the cell wall is collapsed into the cell cavities (Kutnar *et al.* 2009; Şenol and Budakçı 2016). The densification process at low temperatures is not effective, since it requires a greater amount of energy and causes damage to the wood fibers, resulting in a considerable decrease in the mechanical properties (Fang *et al.* 2012; Popescu *et al.* 2014). For this reason, the densification temperature typically is close to the glass transition temperature (T_g), which reduces the stiffness of the material and provides better results (Wolcott 1989; Arruda and Del Menezzi 2013; Laine *et al.* 2014; Tu *et al.* 2014). As the pressing time increases, the wood material is exposed to the temperature for a longer time and thus reaches higher compression ratios compared to those exposed to the same temperature for a shorter period of time (Inoue *et al.* 1993). Similarly, higher compression ratios can be achieved as the press pressure increases (Cloutier *et al.* 2008).

Kutnar *et al.* (2008) reported that the viscoelastic thermal compression (VTC) process increases the bending strength of hybrid poplar. They also reported that the bending properties increased linearly as the amount of densification was increased. Skyba *et al.* (2009) indicated that thermo-hydro-mechanical (THM) densification exerted a positive effect on the bending properties of spruce and beech woods.

Thermo-Vibro-Mechanical® (TVM) densification, as a new and environmentally friendly wood densification method, can be defined as the process of the densification of a material under a certain temperature, pressure, and frequency of vibration. It requires less energy compared to other modification methods. This method can be described as a surface densification method since it is especially effective on the outer parts of the wood. It was also reported that there was a serious change in the surface properties of the materials condensed with TVM, including its density, hardness, glossiness, abrasion, and swelling resistance (Şenol and Budakçı 2016; Şenol *et al.* 2017; Budakçı *et al.* 2021). In this study,

the bending strength (BS), modulus of elasticity (MOE), and compression strength (CS) in the direction parallel to the fiber of Uludağ fir and black poplar specimens densified in the radial and tangential directions *via* the TVM method were investigated.

EXPERIMENTAL

Materials

In the study, Uludağ fir (*Abies bornmüelleriana* Mattf.) and black poplar (*Populus nigra* L.) woods, which are widely used in the furniture industry, were analyzed. It was taken into consideration that the wood, procured in the form of logs from a local forest management office in the Kütahya province of Turkey, would be robust with no growth defects or decay. Flawless wood pieces were cut into samples with dimensions of 360 (length) mm × 60 (width) mm × 21 (thickness) mm from sapwood, according to Turkish standard TS 2470 (1976). These samples were subjected to technical drying at a temperature of 20 °C ± 2 °C with a relative humidity of 65% ± 3% to achieve an air-dried moisture content of 12%, as per TS standard 2471 (1976). Conditioned samples were cut to a draft size according to the standards of the applied tests and then sanded with 100-grit sandpaper *via* a calibrated sanding machine (Version 1100 Melkuç Machine Company, Ankara, Turkey).

Afterwards, prior to TVM densification, the samples were impregnated with Akzo Nobel Kemipol brand-unicolor light walnut color (Catalog color-H 108 8001) aniline-based wood stain and Dewilux Dewitex 129-0174-52 brand colorless alkyd resin-based wood preservative using a 15 s dipping method. Since the wood stain was mixed with distilled water (85% solution), the wood preservative was applied without modification. The samples were conditioned again to eliminate any differences in humidity occurring after these processes. A total of 6084 samples were prepared for 507 different groups, which each contained 12 independent samples.

Thermo-Vibro-Mechanic® (TVM) Densification

The TVM densification process was carried out by applying constant linear vibration at a 3 mm amplitude and a 100 Hz frequency at three different temperatures (100 °C ± 3 °C, 120 °C ± 3 °C, and 140 °C ± 3 °C), three different pressures (0.60 MPa, 1.00 MPa, and 1.40 MPa) and three pressing duration levels (20 s, 60 s, and 100 s) as a result of preliminary trials and experiments. In addition, other studies in the field of wood densification were used in parameter selection (Rautkari *et al*. 2008, 2009). For this process, the samples were placed on the TVM press, which was specifically designed and manufactured within the scope of the research. They were first kept under positive low-pressure conditions (0.2 MPa) so that both surfaces were in contact with the press table. The samples remained in this position until their internal temperature reached the target temperature *via* checking with a digital thermometer (Fig. 1). Then, the target pressure was applied together, which included the vibration.

Except for the control group, half of the samples were densified in the tangential direction, while the other half were densified in the radial direction, in order to observe the effect of the direction of densification on the mechanical properties. At the end of the TVM densification process, the samples were removed from the TVM densification press, and they were cooled to a temperature of 60 °C at a pressure of 0.5 MPa to eliminate any spring-back effect. The samples were then kept in a conditioning cabinet (Fig. 2) at a temperature

of 20 °C ± 2 °C with a relative humidity of 65% ± 3% until a constant weight was achieved. After the densification process, the thickness of the samples was approximately 20 mm.

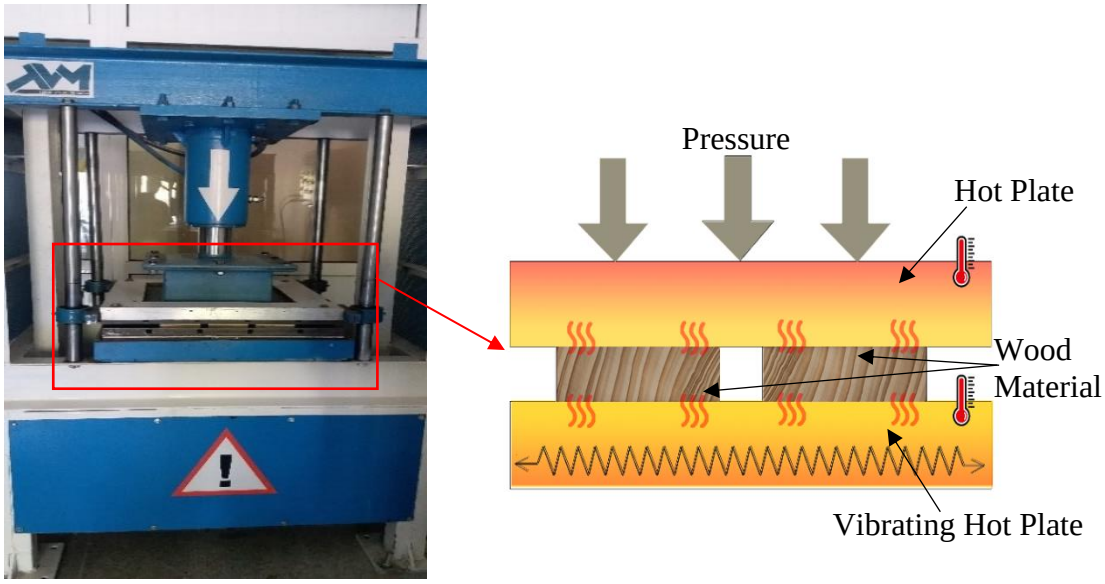

Fig. 1. The TVM densification press and working principle

Fig. 2. Air conditioning and measuring the samples

Methods

Mechanical tests

Mechanical tests were performed to determine the bending strength (BS), modulus of elasticity (MOE), and compression strength (CS) of the prepared samples (as shown in Fig. 3). The BS and MOE values of the samples were determined using a UTEST 7012 (UTEST Material Testing Equipment, Ankara, Turkey) (at 50 kN) test device in accordance with TS standard 2474 (1976) and TS standard 2478 (1976), respectively. They were calculated according to Eqs. 1 and 2, respectively,

$$MOE\ (\mathrm{N/mm^2}) = PL^3 / 4bh^3 f \quad (1)$$

$$BS\ (\mathrm{N/mm^2}) = 3P_{max} L / 2bh^2 \quad (2)$$

where P is the difference between the mean of the lower and upper limits of the force (N), b and h are the width and height of the sample (mm), respectively, f is the displacement at the point of fracture (mm), L is the span between the bearings (mm), and P_{max} is the fracture force (N).

The CS tests were conducted according to ISO standard 13061-17 (2017), while the CS was calculated according to Eq. 3,

$$CS\ (\mathrm{N/mm^2}) = P_{max} / bh \quad (3)$$

where P_{max} is the maximum force (N) applied to the specimen, and b and h are the width and height (mm) of the samples, respectively.

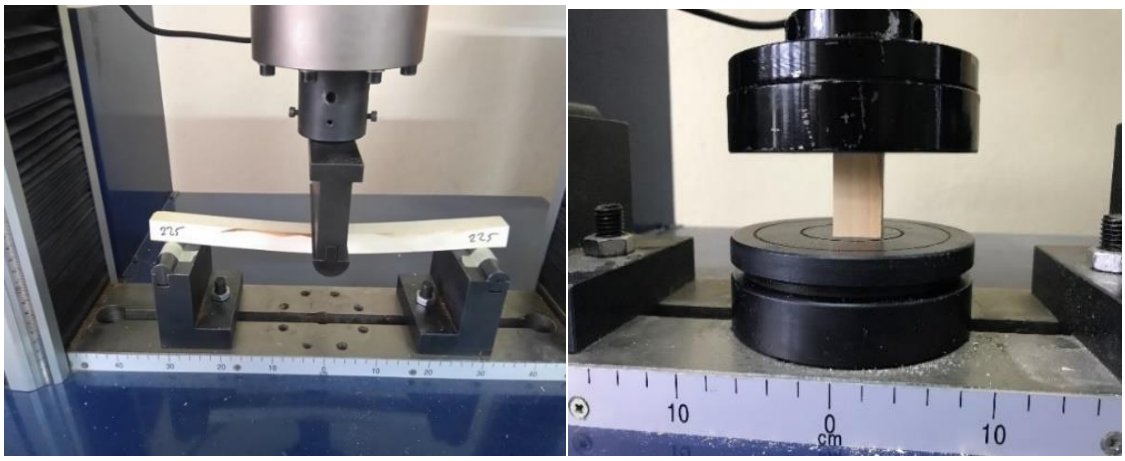

Fig. 3. Testing the bending strength and compression strength

Statistical analysis

The SPSS 22 statistical package program (IBM Corp., Armonk, NY) was used to analyze the data gathered in this study. The effects of the wood type, sectional direction, surface process, densification factors, and the interactions of these factors of each sample on the BS, MOE, and CS were determined *via* a multivariate analysis of variance (ANOVA) test. Comparisons were applied using Duncan's multiple range test (DMRT) and least significant difference (LSD) critical values, while the factors causing the differences were examined as well.

RESULTS AND DISCUSSION

Bending Strength (BS)

The arithmetic means were obtained to determine the effect of the TVM densification process on the BS in terms of the wood type, sectional direction, surface process, and densification factors. Afterwards, an ANOVA test was performed to determine the factors causing the difference. The test results are provided in Table 1.

According to the ANOVA, all factors and their mutual interactions were determined to be significant (p-value less than or equal to 0.05) with respect to the BS. Table 2 lists the DMRT comparison results with respect to the wood type, sectional direction, surface process, and densification factors using the LSD critical value.

Table 1. Results of the ANOVA of the Bending Strength (BS) Values

Factors	Degrees of Freedom	Sum of Squares	Mean Square	F Value	Level of Significance (*p*-value less than or equal to 0.05)
Wood type (A)	1	518.835	518.835	20.569	0.000*
Sectional direction (B)	1	4173.822	4173.822	165.467	0.000*
Surface process (C)	2	10868.249	5434.125	215.431	0.000*
Densification (D)	27	25974.029	962.001	38.138	0.000*
Interaction (AB)	1	673.406	673.406	26.697	0.000*
Interaction (AC)	2	760.153	380.076	15.068	0.000*
Interaction (AD)	27	7347.510	272.130	10.788	0.000*
Interaction (BC)	2	217.118	108.559	4.304	0.014*
Interaction (BD)	27	5758.918	213.293	8.456	0.000*
Interaction (CD)	54	11784.319	218.228	8.651	0.000*
Interaction (ABC)	2	1097.815	548.907	21.761	0.000*
Interaction (ABD)	27	6141.164	227.451	9.017	0.000*
Interaction (ACD)	54	13794.829	255.460	10.127	0.000*
Interaction (BCD)	54	18578.445	344.045	13.639	0.000*
Interaction (ABCD)	54	21091.987	390.592	15.485	0.000*
Error	1680	42377.057	25.224		
Total	2016	171157.655			
Note: *Significant at 95% confidence level					

According to Table 2, the BS value was highest in the black poplar samples (80.4 N/mm^2) while it was lowest in the fir (79.4 N/mm^2). It was highest in the tangential direction (81.3 N/mm^2) and lowest in the radial direction (78.4 N/mm^2) with respect to the sectional direction. In addition, it was highest in the wood preservative applied samples (83.2 N/mm^2) while it was lowest in the aniline dye applied samples (78.90 N/mm^2) with respect to the surface process. It was highest in the samples where TVM densification was applied at a temperature of 140 °C, a pressure of 1.4 MPa, and duration of 100 s (87.5 N/mm^2), while it was lowest in samples without densification (control) (71.9 N/mm^2) with respect to the densification.

Regarding the wood type factor, higher BS values were obtained in the poplar samples compared to the fir samples. After undergoing the TVM densification process, the BS increased up to 41% in the fir samples and 30% in the poplar samples compared to the control samples. The higher BS increase in the poplar samples may have resulted from the low density, diffuse-porous, and coarse-textured structure of this material. For this reason, densification with compression is considered to be more appropriate.

Table 2. The DMRT Comparison Results Considering the Bending Strength (BS) With Respect to the Wood Type, Sectional Direction, Surface Process, and Densification Factor (N/mm^2)

Wood Type	Mean (x̄)	HG
Uludağ fir	79.378	B
Black poplar	80.393	A*
LSD ± 0.158		
Sectional direction	Mean (x̄)	HG
Tangential	81.324	A*
Radial	78.447	B
LSD ± 0.158		
Surface process	Mean (x̄)	HG
Natural	78.543	B
Aniline	77.962	C
Wood protective	83.152	A*
LSD ± 0.194		
Densification	Mean (x̄)	HG
Control	70.584	J
100 °C-0.6 MPa-20s	71.936	J
100 °C-0.6 MPa-60s	77.078	I
100 °C-0.6 MPa-100s	77.191	I
100 °C-1.0 MPa-20s	79.534	FGH
100 °C-1.0 MPa-60s	77.625	I
100 °C-1.0 MPa-100s	80.566	DEFG
100 °C-1.4 MPa-20s	77.184	I
100 °C-1.4 MPa-60s	78.957	GHI
100 °C-1.4 MPa-100s	82.288	CD
120 °C-0.6 MPa-20s	77.804	HI
120 °C-0.6 MPa-60s	80.480	DEFG
120 °C-0.6 MPa-100s	80.351	EFG
120 °C-1.0 MPa-20s	77.805	HI
120 °C-1.0 MPa-60s	80.921	CDEF
120 °C-1.0 MPa-100s	78.188	HI
120 °C-1.4 MPa-20s	82.428	CD
120 °C-1.4 MPa-60s	82.331	CD
120 °C-1.4 MPa-100s	84.339	B
140 °C-0.6 MPa-20s	78.168	HI
140 °C-0.6 MPa-60s	80.794	DEFG
140 °C-0.6 MPa-100s	82.817	BC
140 °C-1.0 MPa-20s	77.593	I
140 °C-1.0 MPa-60s	81.979	CDE
140 °C-1.0 MPa-100s	81.758	CDE
140 °C-1.4 MPa-20s	82.240	CDE
140 °C-1.4 MPa-60s	86.378	A
140 °C-1.4 MPa-100s	87.474	A*
LSD ± 0.592		
Note: x̄ = Arithmetic mean; HG = homogeneity group; and * = the highest fully dried density		

With respect to the sectional direction factor, higher BS values were obtained in the tangential direction compared to the radial direction. After undergoing the TVM densification process, the BS increased up to 38.1% in the tangential direction and 22.3% in the radial direction compared to the control samples. Previous studies indicated that different results were obtained from the radial and tangential compression of wood depending on its anisotropic structure. It was also reported that the probable reason for the samples in the tangential direction having a higher BS value is the spring and summerwood layers, which have different densities before compression but have similar densities after densification (Blomberg *et al.* 2005; Marttila *et al.* 2016).

The highest BS with regards to the surface process factor was obtained in the samples treated with wood preservatives. After undergoing the TVM densification process, the BS increased up to 36% in samples treated with wood preservative, 31.4% in untreated (but densified) samples, and 26% in samples treated with aniline dye when compared to the undensified and untreated control samples. This increase may be due to the plasticizer property of the oil alkyd used as the main binder resin in wood preservative. Previous studies stated that oil-based impregnates have a flexible structure and can adapt to dimensional changes in wood (Budakçı and Togay 2002).

At the densification factor level, an increase varying from 13% to 52% was found in the BS values compared to the control samples. The highest BS values were obtained from samples under the following conditions: high temperatures (140 °C), high pressure (1.4 MPa), and longer durations (60 s and 100 s). Previous studies emphasized that the density increases as the compression ratio increases, which results in the increase of some of the mechanical properties of the wood (Tabarsa and Chui 1997; Blomberg *et al.* 2005; Ülker *et al.* 2012; Pelit 2014; Marttila *et al.* 2016)

The DMRT comparison and interaction of the results performed with respect to the level of wood type, sectional direction, surface process, and densification factors are provided in Figs. 4 and 5 to illustrate the results of single comparisons.

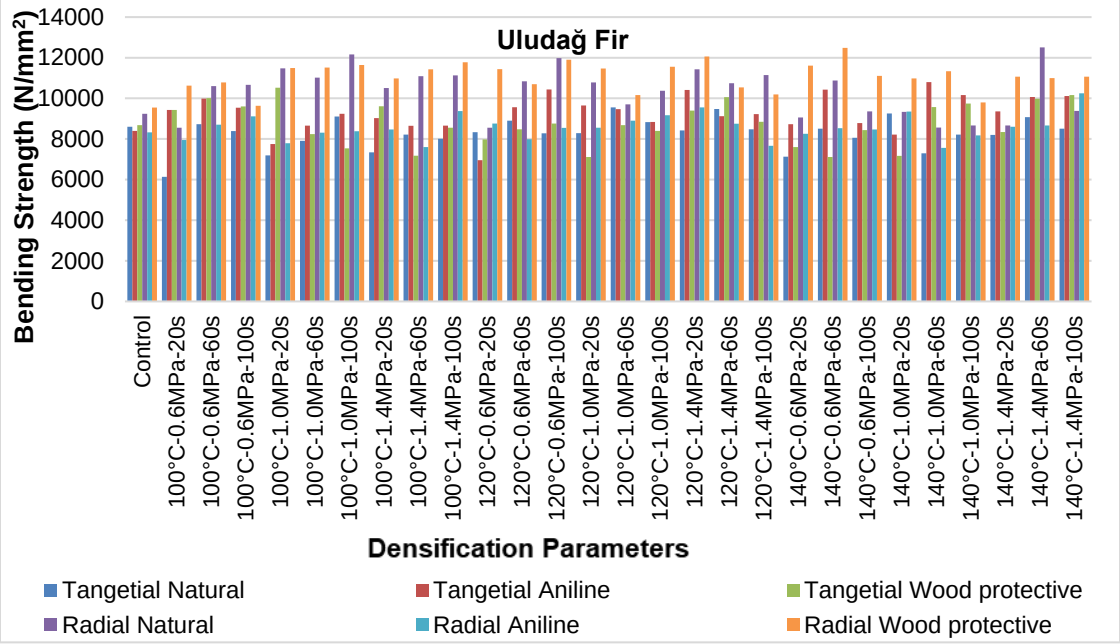

Fig. 4. The DMRT comparison results for the BS values with respect to the wood type, sectional direction, surface process, and densification interaction level

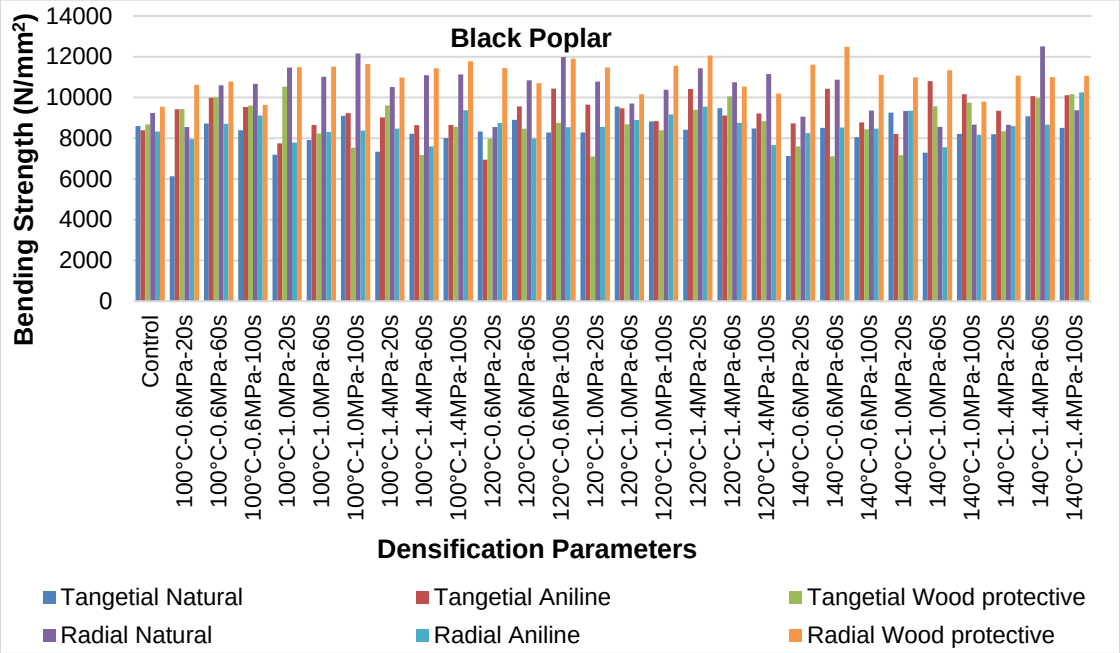

Fig. 5. The DMRT comparison results for the BS values with respect to the wood type, sectional direction, surface process, and densification interaction level

The results in Figs. 4 and 5 indicate that the highest BS value (103.9 N/mm^2) was obtained from the tangential direction poplar samples that were treated with wood preservative and underwent TVM densification at a pressure of 1.4 MPa, a temperature of 140 °C, and a duration of 100 s.

The lowest value (60.1 N/mm^2) was obtained from the undensified radial direction black poplar samples that were treated with aniline dye. The BS increased depending on the TVM densification parameters, and higher values were determined as the compression ratio and application time increased.

Modulus of Elasticity (MOE)

In order to determine the effect of the TVM densification process on the MOE in terms of the wood type, sectional direction, surface process, and densification factors, the arithmetic means were obtained. Afterwards, an ANOVA test was performed to determine the possible factors causing the difference. The test results are provided in Table 3.

According to the ANOVA, all factors and their mutual interactions were significant (p-value less than or equal to 0.05) with respect to the MOE. Table 4 shows the DMRT comparison results with respect to the wood type, sectional direction, surface process, and densification factors using the LSD critical value.

The results in Table 4 show that the MOE value was highest in the black poplar samples (9440 N/mm^2), while it was lowest in the fir (9380 N/mm^2) with respect to the wood type. It was highest in the tangential direction (9780 N/mm^2) and lowest in the radial direction (9040 N/mm^2) with respect to the sectional direction. In addition, it was highest in the wood preservative applied samples (9720 N/mm^2), while it was lowest (9140 N/mm^2) in the aniline dye applied ones with respect to the surface process.

Table 3. The ANOVA Results of the Modulus of Elasticity (MOE) Values

Factors	Degrees of Freedom	Sum of Squares	Mean Square	F Value	Level of Significance (p-value less than or equal to 0.05)
Wood type (A)	1	2147900.008	2147900.008	4.598	0.032*
Sectional direction (B)	1	273107527.9	273107527.9	584.577	0.000*
Surface process (C)	2	116277412.4	58138706.22	124.444	0.000*
Densification (D)	27	266148920.1	9857367.412	21.099	0.000*
Interaction (AB)	1	108769179.6	108769179.6	232.816	0.000*
Interaction (AC)	2	57880478.4	28940239.20	61.946	0.000*
Interaction (AD)	27	115355562.4	4272428.235	9.145	0.000*
Interaction (BC)	2	16558073.82	8279036.911	17.721	0.000*
Interaction (BD)	27	104902587.4	3885281.014	8.316	0.000*
Interaction (CD)	54	224331430.2	4154285.744	8.892	0.000*
Interaction (ABC)	2	960736398.5	480368199.2	1028.211	0.000*
Interaction (ABD)	27	193401147.8	7163005.474	15.332	0.000*
Interaction (ACD)	54	390934252	7239523.185	15.496	0.000*
Interaction (BCD)	54	239049344.8	4426839.719	9.475	0.000*
Interaction (ABCD)	54	350790751.4	6496125.026	13.905	0.000*
Error	1680	784876713.3	467188.520		
Total	2016	182680260540			
Note: *Significant at 95% confidence level					

The MOE was also the highest in the samples where TVM densification was applied at a temperature of 140 °C, a pressure of 1.4 MPa, and a duration of 100 s (10200 N/mm^2) while it was lowest in samples without densification, *i.e.*, the control, (8660 N/mm^2) with respect to the densification.

Table 4. The DMRT Comparison Results Considering the Modulus of Elasticity (MOE) With Respect to the Wood Type, Sectional Direction, Surface Process, and Densification Factor (N/mm^2)

Wood Type	Mean (x̄)	HG
Uludağ fir	9376.358	B
Black poplar	9441.640	A*
LSD ± 21.529		
Sectional Direction	Mean (x̄)	HG
Tangential	9777.062	A*
Radial	9040.937	B
LSD ± 21.529		
Surface Process	Mean (x̄)	HG
Natural	9359.946	B
Aniline	9142.473	C
Wood protective	9724.577	A*
LSD ± 26.367		
Densification	Mean (x̄)	HG
Control	8663.667	M
100 °C-0.6 MPa-20s	8759.653	LM
100 °C-0.6 MPa-60s	9498.389	DEFG
100 °C-0.6 MPa-100s	9522.444	DEF
100 °C-1.0 MPa-20s	9201.639	HIJK
100 °C-1.0 MPa-60s	9454.389	DEFGH
100 °C-1.0 MPa-100s	9570.194	DE
100 °C-1.4 MPa-20s	9103.444	JK
100 °C-1.4 MPa-60s	9185.056	IJK
100 °C-1.4 MPa-100s	9860.278	BC
120 °C-0.6 MPa-20s	8957.389	KL
120 °C-0.6 MPa-60s	9492.75	DEFG
120 °C-0.6 MPa-100s	9673.333	CD
120 °C-1.0 MPa-20s	9274.778	FGHIJ
120 °C-1.0 MPa-60s	9575.806	DE
120 °C-1.0 MPa-100s	9283.222	FGHIJ
120 °C-1.4 MPa-20s	9981.167	AB
120 °C-1.4 MPa-60s	9632.611	CDE
120 °C-1.4 MPa-100s	9456.333	DEFGH
140 °C-0.6 MPa-20s	9241.528	GHIJ
140 °C-0.6 MPa-60s	9285.111	FGHIJ
140 °C-0.6 MPa-100s	9377.833	EFGHI
140 °C-1.0 MPa-20s	8955.556	KL
140 °C-1.0 MPa-60s	9258.139	FGHIJ
140 °C-1.0 MPa-100s	9241.278	GHIJ
140 °C-1.4 MPa-20s	9556.528	DE
140 °C-1.4 MPa-60s	10174.972	A*
140 °C-1.4 MPa-100s	10214.486	A*
LSD ± 80.553		
Note: x̄ = Arithmetic mean; HG = homogeneity group; and * = the highest fully dried density		

Regarding the wood type factor, higher MOE values were obtained in the poplar samples compared to the fir samples. After undergoing the TVM densification process, the MOE increased up to 34% in fir samples and 25% in poplar samples when compared to the control samples.

From the sectional direction factor standpoint, higher MOE values were obtained in the tangential direction compared to the radial direction. After undergoing the TVM densification process, the MOE increased up to 28.2% in the tangential direction and 17.6% in the radial direction when compared to the control samples. Previous studies stated that the density of a wood material provides an idea about its properties and usage possibilities. It was also indicated that the increase in density may have a positive effect on the MOE (Kollmann and Côté 1968; Marttila *et al.* 2016).

The highest MOE with respect to the surface process factor was obtained in the samples treated with wood preservatives. After undergoing the TVM densification process, the MOE increased up to 32.9% in samples treated with wood preservative, 22.3% in untreated (but densified) samples, and 22.5% in samples treated with aniline dye when compared to the undensified and untreated control samples. The results were in parallel with the findings of the BS tests. At the densification factor level, an increase varying from 11% to 50% was obtained for the MOE values in comparison to the control samples depending on TVM densification parameters. The highest MOE values were attained from samples under the following conditions: high temperature (140 °C), high pressure (1.4 MPa), and longer compression time (60 s and 100 s). A positive linear relationship between the densification ratio and the density value with the MOE has been reported in the literature (Kurtoğlu 1984; Tabarsa and Chui 1997; Marttila *et al.* 2016). In addition, the compression ratio has been declared as the most important factor affecting the MOE after the densification process and the compression temperature has been stated as not important (Lamason and Gong 2007; Pelit 2014).

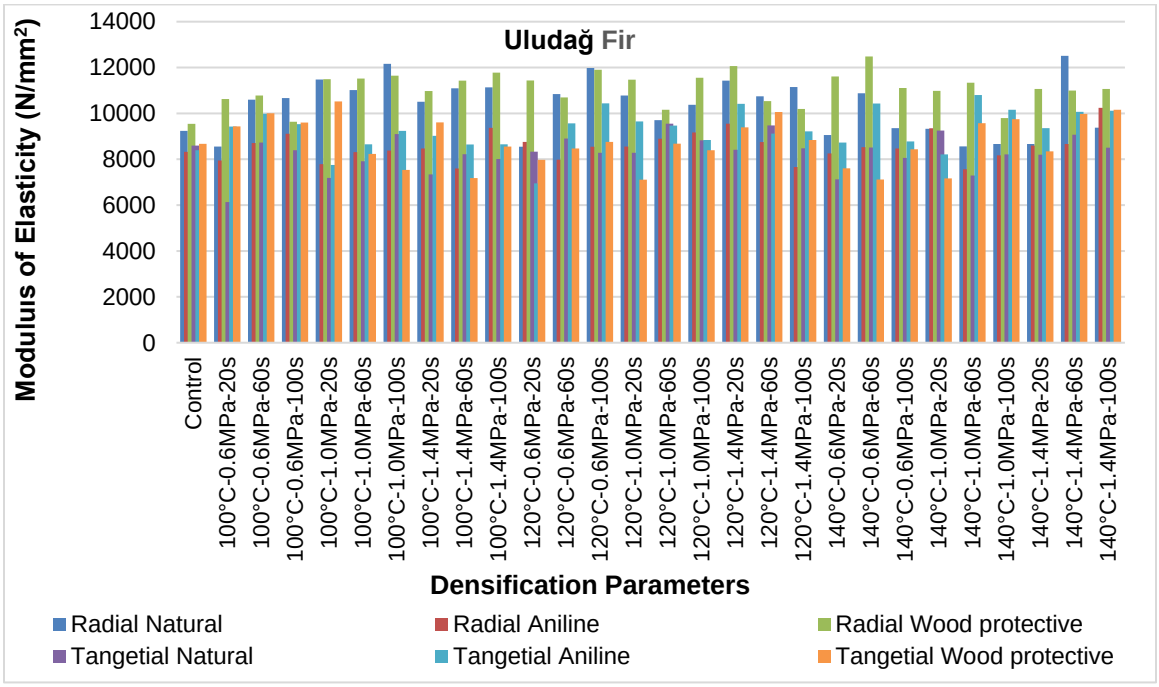

Fig. 6. The DMRT comparison results for the MOE values with respect to the wood type, sectional direction, surface process, and densification interaction level

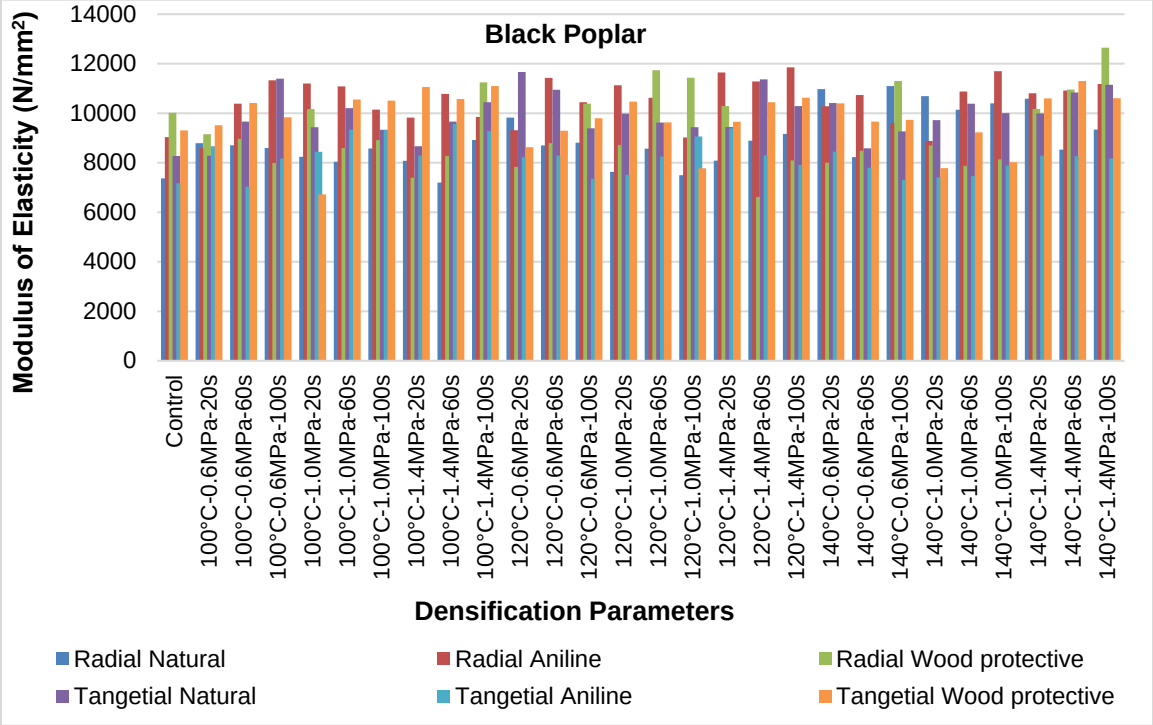

Fig. 7. The DMRT comparison results for the MOE values with respect to the wood type, sectional direction, surface process, and densification interaction level

The DMRT comparison and interaction of the results performed with respect to the wood type, sectional direction, surface process, and densification factors are provided in Figs. 6 and 7 to illustrate the results of single comparisons.

According to Figs. 6 and 7, the highest MOE value (12,600 N/mm^2) was obtained from the tangential direction poplar samples that were treated with wood preservative and underwent TVM densification at 1.4 MPa and 140 °C for 100 s.

The lowest value (6130 N/mm^2) was obtained from the radial direction untreated fir samples that underwent TVM densification at a pressure of 0.6 MPa, a temperature of 100 °C, and a duration of 20 s. The MOE increased depending on the TVM densification parameters while higher values were obtained as the compression ratio and application time increased.

Compression Strength (CS)

The arithmetic means were obtained to examine the effect of the TVM densification process on the CS in terms of the wood type, sectional direction, surface process, and densification factors. Afterwards, an ANOVA test was performed to determine the factors causing the difference. The test results are shown in Table 5.

According to the ANOVA, all factors and their mutual interactions were significant (*p*-value less than or equal to 0.05) with respect to the CS. Table 6 shows the DMRT comparison results with respect to the wood type, sectional direction, surface process, and densification factors using the LSD critical value.

Table 5. ANOVA Results of the Compression Strength (CS) Values

Factors	Degrees of Freedom	Sum of Squares	Mean Square	*F* Value	Level of Significance (*p*-value less than or equal to 0.05)
Wood type (A)	1	3492.417	3492.417	258.056	0.000*
Sectional direction (B)	1	2698.758	2698.758	199.412	0.000*
Surface process (C)	2	808.334	404.167	29.864	0.000*
Densification (D)	27	8486.377	314.31	23.224	0.000*
Interaction (AB)	1	105.14	105.14	7.769	0.005*
Interaction (AC)	2	614.995	307.498	22.721	0.000*
Interaction (AD)	27	3090.305	114.456	8.457	0.000*
Interaction (BC)	2	535.073	267.536	19.768	0.000*
Interaction (BD)	27	2672.341	98.976	7.313	0.000*
Interaction (CD)	54	5086.4	94.193	6.960	0.000*
Interaction (ABC)	2	241.334	120.667	8.916	0.000*
Interaction (ABD)	27	2047.942	75.85	5.605	0.000*
Interaction (ACD)	54	4367.393	80.878	5.976	0.000*
Interaction (BCD)	54	5580.538	103.343	7.636	0.000*
Interaction (ABCD)	54	6789.875	125.738	9.291	0.000*
Error	1680	22736.416	13.534		
Total	2016	3691124.592			

Note: *Significant at 95% confidence level

According to Table 6, the CS values obtained were the highest in the fir samples (43.7 N/mm^2) and lowest in the poplar (41.1 N/mm^2) with respect to the wood type. It was highest in the tangential direction (43.5 N/mm^2) and lowest in the radial direction (41.2 N/mm^2) with respect to the sectional direction. When the surface process was taken into account, the CS was highest in the wood preservative applied samples (43.0 N/mm^2) and lowest in the aniline dye applied samples (41.5 N/mm^2). In addition, it was highest in the samples where TVM densification was applied at a temperature of 140 °C, a pressure of 1.4 MPa, and a duration of 100 s (46.8 N/mm^2), while it was lowest in samples without densification (control) (37.198 N/mm^2).

Table 6. The DMRT Comparison Results Considering the Compression Strength (CS) With Respect to the Wood Type, Sectional Direction, Surface Process, and Densification Factor (N/mm^2)

Wood Type	Mean (x̄)	HG
Uludağ fir	43.701	A*
Black poplar	41.069	B
LSD ± 0.116		
Sectional Direction	Mean (x̄)	HG
Tangential	43.542	A*
Radial	41.228	B
LSD ± 0.116		
Surface Process	Mean (x̄)	HG
Natural	42.582	B
Aniline	41.530	C
Wood protective	43.044	A*
LSD ± 0.142		
Densification	Mean (x̄)	HG
Control	37.198	M
100 °C-0.6 MPa-20s	38.049	M
100 °C-0.6 MPa-60s	41.260	IJKL
100 °C-0.6 MPa-100s	41.773	HIJK
100 °C-1.0 MPa-20s	41.021	JKL
100 °C-1.0 MPa-60s	40.239	L
100 °C-1.0 MPa-100s	43.037	DEFGH
100 °C-1.4 MPa-20s	41.094	JKL
100 °C-1.4 MPa-60s	42.229	GHIJ
100 °C-1.4 MPa-100s	43.833	DE
120 °C-0.6 MPa-20s	41.259	IJKL
120 °C-0.6 MPa-60s	42.828	DEFGH
120 °C-0.6 MPa-100s	40.955	JKL
120 °C-1.0 MPa-20s	42.564	EFGHI
120 °C-1.0 MPa-60s	43.637	DEFG
120 °C-1.0 MPa-100s	41.750	HIJK
120 °C-1.4 MPa-20s	43.005	DEFGH
120 °C-1.4 MPa-60s	43.593	DEFG
120 °C-1.4 MPa-100s	43.940	DE
140 °C-0.6 MPa-20s	41.947	HIJK
140 °C-0.6 MPa-60s	40.601	KL
140 °C-0.6 MPa-100s	43.711	DEF
140 °C-1.0 MPa-20s	42.610	EFGHI
140 °C-1.0 MPa-60s	44.064	CD
140 °C-1.0 MPa-100s	42.376	FGHIJ
140 °C-1.4 MPa-20s	46.171	AB
140 °C-1.4 MPa-60s	45.227	BC
140 °C-1.4 MPa-100s	46.818	A*
LSD ± 0.434		
Note: x̄ = Arithmetic mean; HG = homogeneity group; and * = the highest fully dried density		

Regarding the wood type factor, higher CS values were obtained from the fir samples compared to the poplar samples. After undergoing the TVM densification process, the CS increased up to 29.4% in poplar samples and 23.0% in fir samples compared to the control samples.

Such a result may depend on the fact that fir is a coniferous species, meaning that the regions of the summer wood and spring wood in the annual rings are distinctly different. It has been reported in the literature that the amount of latewood positively affects the hardness, abrasion, and resistance properties of the wood (Kutnar and Sernek 2007; Lamason and Gong 2007; Rautkari *et al.* 2013).

With respect to the sectional direction factor, higher CS values were obtained in the tangential direction compared to the radial direction. After undergoing the TVM densification process, the CS increased up to 33.0% in the tangential direction and 23.5% in the radial direction when compared to the control samples. In addition, it has been stated in the literature that the strength properties of densified wood material are improved compared to untreated wood and this increase is generally proportional to the increase in density (Morsing 2000; Pelit 2014).

The highest CS value with respect to the surface process factor was obtained from the samples treated with wood preservatives. After undergoing the TVM densification process, the CS increased up to 35% in samples treated with wood preservative, 33.5% in untreated (but densified) samples, and 28.2% in samples treated with aniline dye compared to the undensified and untreated control samples. Previous studies have stated that the amount of oil retention and the density values are parallel. In addition, the increment in density considerably increases the CS as well as other strength properties (Bozkurt and Erdin, 1997; Kollmann and Côté 1968). The results of Fourier-transform infrared spectrophotometry (FTIR) analysis showed that only a small part of the wood compositions was degraded, with most of their structure being preserved. The oil absorption of wood may also have increased the lateral stability by filling the cell gaps and increasing the cell wall thickness.

At the densification factor level, an increase varying from 15% to 67% was observed in the CS values when compared to the control samples. The highest CS values were obtained from samples under the following conditions: high temperature (140 °C), high pressure (1.4 MPa), and longer duration (100 s). The results also showed that the CS increased depending on the TVM densification parameters; higher values were determined as the compression ratio and application time increased. It has been stated in the literature that the increase in the strength values of the wood after the densification process is due to the decrease in the void volume of the wood material as well as the increase in the load-bearing cell wall per unit volume (Ülker *et al.* 2012). Additionally, it has been reported that the increment in density increases the CS parallel to the fibers, the BS in radial and tangential directions, and the Brinell hardness values (Blomberg *et al.* 2005).

The DMRT comparison and interaction of the results performed with respect to the wood type, sectional direction, surface process, and densification factors are provided in Figs. 8 and 9 to illustrate the results of single comparisons.

The results in Figs. 8 and 9 show that the highest CS value (52.7 N/mm^2) was obtained from the tangential direction untreated poplar samples that underwent TVM densification at a pressure of 1.4 MPa, a temperature of 140 °C, and a duration of 100 s. The lowest value (29.5 N/mm^2) was obtained from undensified radial direction black poplar samples that were treated with aniline dye. The CS increased depending on the TVM densification parameters, while higher values were obtained as the compression ratio and application time increased.

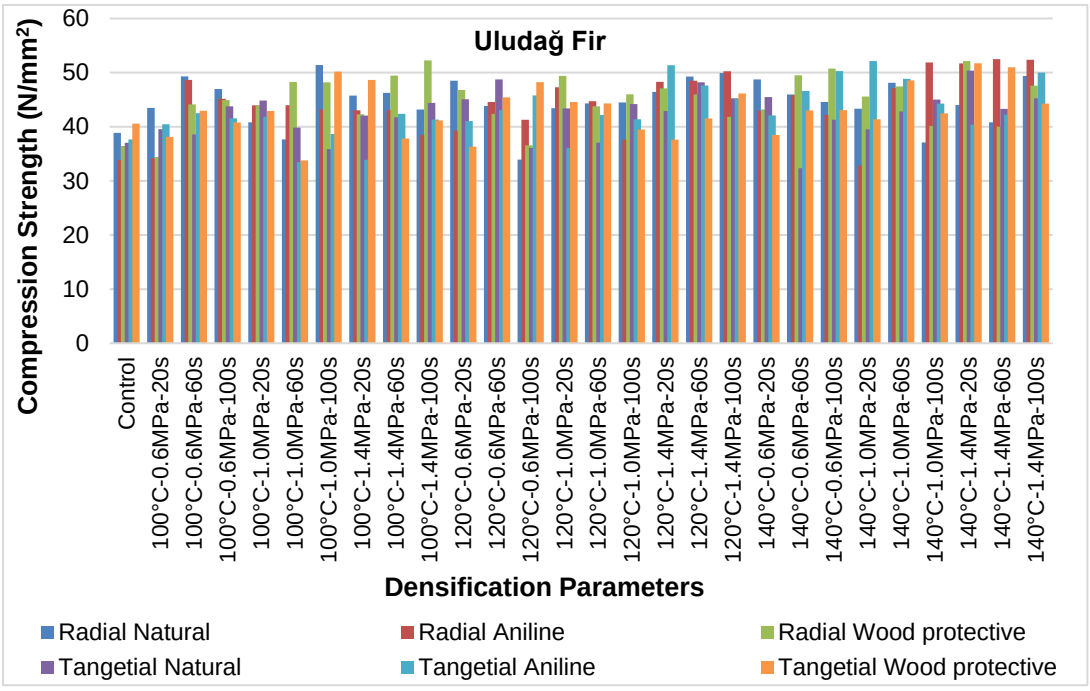

Fig. 8. The DMRT comparison results for the CS values with respect to the wood type, sectional direction, surface process, and densification interaction level

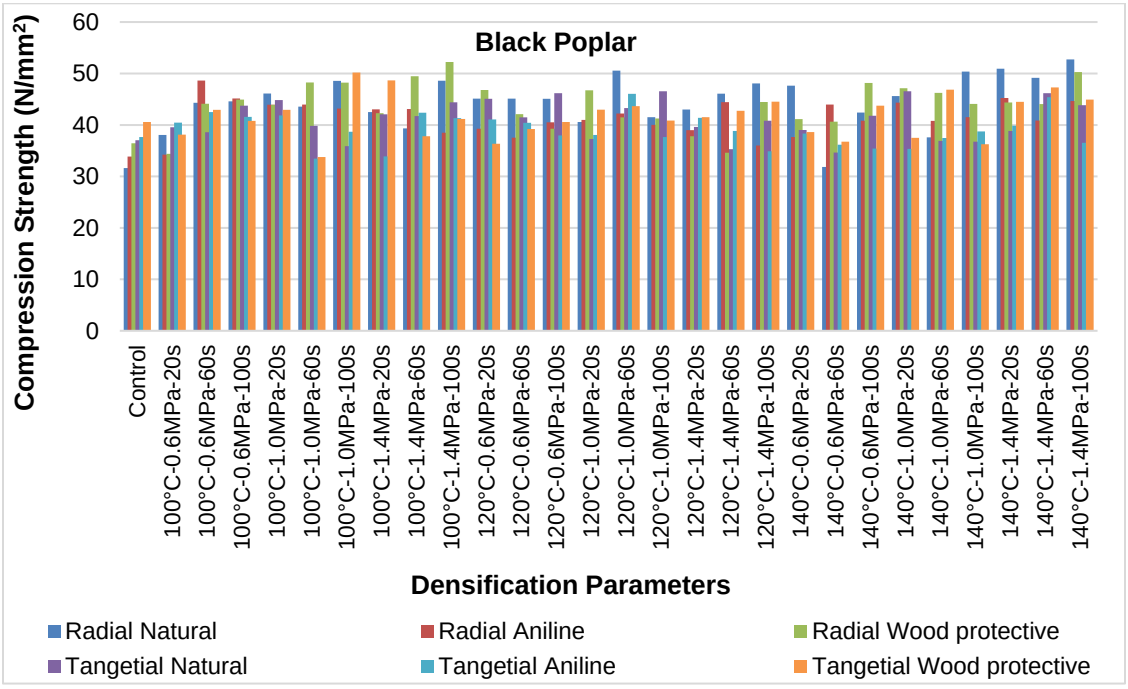

Fig. 9. The DMRT comparison results for the CS values with respect to the wood type, sectional direction, surface process, and densification interaction level

CONCLUSIONS

1. This study developed an innovative and environmentally friendly new method called Thermo-Vibro-Mechanic® (TVM) densification as an alternative to densification and thermal modification processes to obtain wood material with high performance by improving the resistance characteristics of low-density wood types.
2. Densification with TVM increased the bending strength (BS) and modulus of elasticity (MOE) values up to 50% and the CS value up to 67%.
3. Generally, the highest mechanical properties were obtained in the samples that underwent TVM densification at the highest pressure (1.4 MPa), temperature (140 °C), and duration (100 s).
4. It was observed that the TVM densification process caused a noticeable improvement in the mechanical properties of fast-growing and low-density woods. The study has particular value in the TVM process. It is a new method and provides an alternative contribution to the use of fast-growing low-density species with relatively low commercial value.
5. Although densification *via* the TVM method especially affected the parts of the samples near the surface, it also caused a notable improvement in the mechanical properties. In this respect, it can be claimed that the mechanical properties were improved by consuming less energy compared to methods that completely densified the wood.

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