Effects of Thermo-Vibro-Mechanic® Densification on the Density and Swelling of Pre-Treated Uludağ Fir and Black Poplar Wood

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The radial and tangential swelling as well as the fully dried density of low-density wood materials densified *via* the Thermo-Vibro-Mechanic® method were evaluated in response to applying wood stain and preservative. The samples obtained from Uludağ fir (*Abies bornmüelleriana* Mattf.) and black poplar (*Populus nigra* L.) in the radial and tangential direction were pre-treated with wood stain and preservative before undergoing Thermo-Vibro-Mechanic® densification. Thermo-Vibro-Mechanic® densification was performed at three different temperatures (100 °C ± 3 °C, 120 °C ± 3 °C, and 140 °C ± 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). Afterwards, changes in the fully dried density and swelling amounts in the radial and tangential directions of the samples were determined. The fully dried density increased by 15.4% to 38% and the radial and tangential swelling amounts increased by 73.2% to 242.6%, when the densified samples were compared to the control samples. In general, the fully dried density and swelling values increased depending on the Thermo-Vibro-Mechanic® densification parameters; higher values were found as the compression ratio and total application time increased.

Keywords: Thermo-Vibro-Mechanic® (TVM) densification; Wood stain; Wood preservative; Density; Swelling

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INTRODUCTION

Most of the mechanical properties of wood materials are related to their density (Blomberg and Persson 2004; Kamke 2006; Kutnar and Šernek 2007; Rautkari 2012; Budakçı *et al.* 2016; Pelit *et al.* 2017, Şenol and Budakçı 2019). Generally, high-density wood species are preferable for many engineering structures and applications due to their high mechanical strength. However, high-density wood resources are limited and usually expensive (Fang *et al*. 2019). Densification treatments make it possible to increase the density of low or moderate density woods, as well as obtaining a specific strength in densified woods that is higher than most structural metals and alloys. These characteristics make it a low-cost, high-performance, and lightweight alternative compared to other structural materials (Song *et al*. 2018; Fang *et al.* 2019). Since the densification of wood drastically improves its mechanical properties and hardness, multiple studies have been carried out to determine the optimum parameters for proper densification (Blomberg and Persson 2004; Rautkari *et al.* 2008, 2009; Fu *et al*. 2016, 2017; Li *et al.* 2017; Sandberg et al. 2017; Şenol *et al.* 2017; Şenol and Budakçı 2018; Cruz *et al*. 2018; Şenol and Budakçı 2019). With the densification process, low-density woods are converted to high density

woods, therefore making them commercially high-value products. In addition, high-density woods can be made more durable *via* densification (Blomberg *et al.* 2005; Kutnar and Šernek 2007; Ulker *et al.* 2012; Şenol and Budakçı 2019).

The type of material, temperature, softening or plasticizing period, densification method, and amount of pressure are the most important variables in the densification of wood materials. Each of these parameters affects the resistance properties of the wood after the densification process. A different application of these parameters can increase the strength properties of densified wood materials up to 100%. (Ulker *et al.* 2012; Gao *et al*. 2019).

The densification of wood materials *via* compression is based on the principle of collapsing the cell wall, thus reducing the void volume. (Kutnar *et al.* 2009; Budakçı *et al.* 2016). However, breaks and cracks can occur in the cell wall of densified wood material under standard room conditions. The natural elastic structure of the wood plays an important role in the densification process *via* compression. Lignin, which gives the wood its rigidity, exhibits an elastic property when the wood temperature is greater than the glass-transition temperature. Therefore, the densification process above the glass transition temperature can be performed without major deformations in amorphous polymers or cracks in cell walls. Compression properties mostly depend on the density, moisture content, cell wall volume, and compressing direction of the wood. The biggest problem with the densification process is that the compressed woods tend to return to their original dimensions, due to the spring-back effect, when exposed to moisture or water (Seborg *et al.* 1956; Kollmann *et al.* 1975; Kultikova 1999; Morsing 2000; Blomberg *et al.* 2006; Rautkari 2012). However, this problem can be eliminated by using heat and steam during the densification process (Kutnar and Šernek 2007; Rautkari *et al.* 2010; Li *et al.* 2017; Şenol and Budakçı 2019).

The densification of wood without the use of chemicals has been known for a long time. However, due to the plasticization and insufficient dimensional stability of the final products, it has not been widely adopted by industry. Many types of densified wood products have been produced at various times around the world. In addition, due to the increase in environmental awareness in the last quarter-century, there have been restrictions on the usage of environmentally harmful preservatives. This has led to the development of new environmentally friendly methods that preserve the wood against biological degradation and increase its dimensional stability (Korkut and Kocaefe 2009; Şenol and Budakçı 2016). Examples of these methods are as follows: densification using temperature and pressure in an open system, *i.e.*, thermo-mechanical (TM); densification using temperature, pressure, and steam in a closed system, *i.e.*, thermo-hygro-mechanical (THM); densification using temperature and pressure after pre-softening with steam, *i.e.*, viscoelastic-thermal-compression (VTC); and densification using temperature, pressure, and vibration, *i.e.*, thermo-vibro-mechanic® (TVM), which is a new application method (Şenol and Budakçı 2016). The hypothesis behind the TVM densification process is that it is advantageous to reduce the long, cylindrical void spaces, called lumens, in wood cells by heat treatment combined with compression. Unlike other densification techniques, this technique aims to mechanically bond the opposite inner faces of the cell wall on the axis of the densification direction to each other by a vibration effect.

The main aim of the study was to determine the radial and tangential swelling as well as the fully dried density of TVM densification applied pre-treated low-density wood materials. Also, the goal was to obtain more durable wood by improving the strength properties of low-density wood species *via* the TVM densification process, which is an

environmentally friendly new modification method and an alternative to densification and thermal modification processes. For this purpose, a new and special TVM densification press was designed and manufactured. The samples were prepared from Uludağ fir (*Abies Bornmülleriana* Mattf.) and black poplar (*Populus nigra* L.) in the radial and tangential direction. They were pre-treated with wood stain and wood preservative before being densified *via* the TVM method. Lastly, the changes caused by TVM densification in terms of the values of the fully dried density, according to TS standard 2472 (1976), and the swelling in radial and tangential directions, according to TS standard 4084 (1983), were determined. The results of the experiments were analyzed and interpreted.

EXPERIMENTAL

Materials

Preparation of the wooden materials

Uludağ fir (*Abies bornmüelleriana* Mattf.) and black poplar (*Populus nigra* L.), which are widely used in the forest products industry in Turkey, were the preferred species used for the preparation of the samples. It was taken into consideration that the wood, procured in the form of logs from Forest Management in the Kütahya province of Turkey, would be robust with no growth defects or decay. Flawless (as much as possible free from defects such as knots, rot, burl tissue, coarse grain, cracks etc.) wood pieces were cut with dimensions of 360 (length) × 60 (width) × 21 (thickness) mm from sapwood according to TS standard 2470 (1976). These timber samples were subjected to technical drying to achieve an air-dried moisture of 12%. Samples at the specified air-dried moisture percentage 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. Afterwards, prior to TVM densification, the samples 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) using a 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 a temperature of 20 °C ± 2 °C and a relative humidity of 65% ± 3% in order to achieve equilibrium moisture content, as per TS standard 2471 (1976).

TVM densification

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 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, especially designed and manufactured within the scope of the research, were first kept under low positive pressure conditions (0.2 MPa) so that both surfaces were in contact with the press table. The samples remained in this position until the internal temperature of the samples reached the target temperature values *via* checking with a digital thermometer (as shown in Fig. 1).

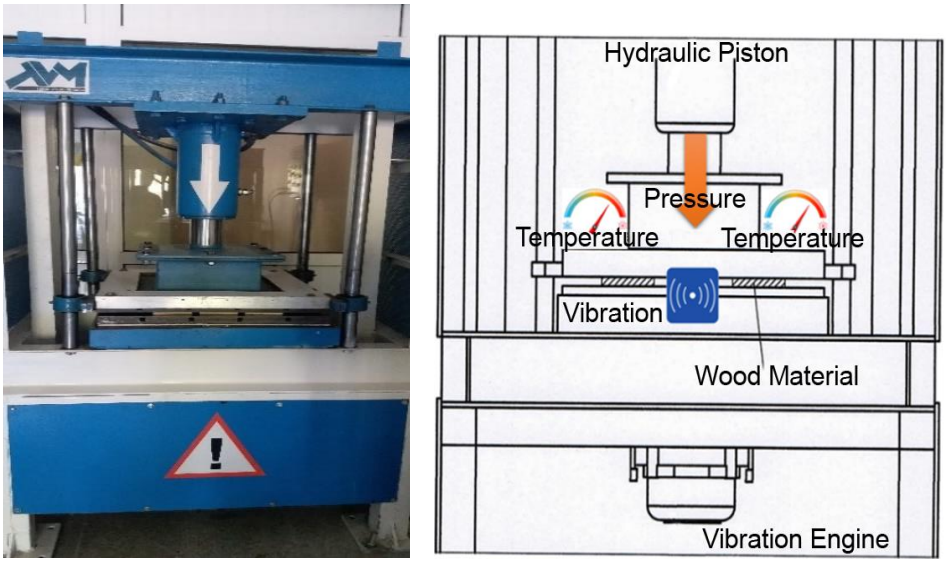

Fig. 1. TVM densification press and working principle (Şenol 2018)

At the end of the TVM densification process, the samples were removed from the TVM density press and cooled to a temperature of 60 °C on a different press (plating press) at a pressure of 0.5 MPa to eliminate any spring-back effect. Then, the samples were kept in the climate chamber at a temperature of 20 °C ± 2 °C temperature and a relative humidity of 65% ± 3%, according to TS standard 2471 (1976), before undergoing testing and they reached a constant weight (Fig. 2). Half of the samples (n=2016) were densified in the tangential and the other half in the radial direction. The final dimensions of samples were 20 mm in width (tangential), 20 mm in height (radial), and 30 mm in length (longitudinal) for both tests. A total of 4032 samples were prepared for 168 different groups, each consisting of 12 samples. Each group was created using different and independent samples.

Fig 2. Fully dried samples and measuring the samples

Methods

Fully dried density

The density measurements in fully dried conditions were made in accordance with TS standard 2472 (1976) procedures. The air-dry samples were kept in an oven at a temperature of 103 °C ± 2 °C until they reached a constant weight. Then, the masses of the samples were determined using an analytical balance with an accuracy of ± 0.01 g, and

their dimensions were measured with a digital caliper with a precision of ± 0.01 mm. Lastly, their volume (*V*) was determined according to Eq. 1,

$$\delta_0 = \frac{M0}{V0} \quad (1)$$

where δ_0 is the fully dried density (g/cm^3), M_0 is the fully dried mass (g), and V_0 is the fully dried volume (cm^3).

Radial and tangential swelling

The determination of the swelling rates of the samples were performed in accordance with TS standard 4084 (1983). Initially, the samples were kept at a temperature of 103 °C ± 2 °C until they reached a constant size and mass. Subsequently, the radial and tangential thicknesses of the samples were determined from their midpoints with a digital caliper with a precision of ± 0.01 mm. Thereafter, samples were placed in a glass aquarium containing distilled water at a temperature of 20 ± 2 °C. A wire mesh was placed over the aquarium so that the samples were completely submerged in water. The position of the samples was changed *via* stirring with a rod at regular intervals (Fig. 3). When the dimensions of the samples became stable, they were taken out of the aquarium and any excess water was gently wiped off. Finally, the radial and tangential thickness were measured again from the first measurement points. The measurements were made in the direction in which the densification was made (Fig 4).

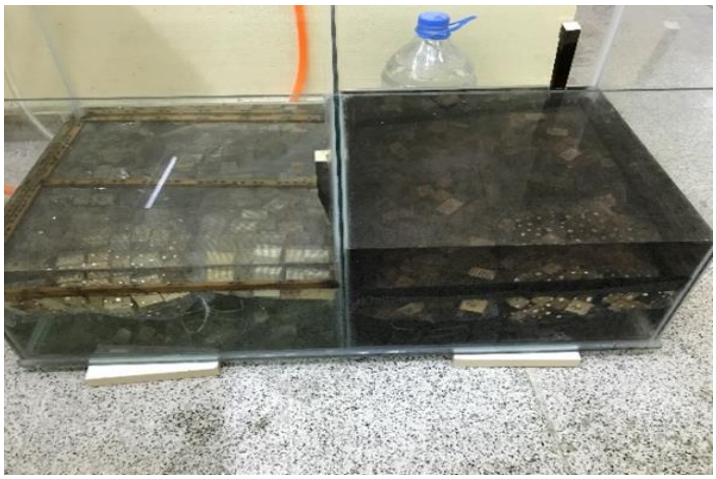

Fig. 3. Soaking samples in distilled water

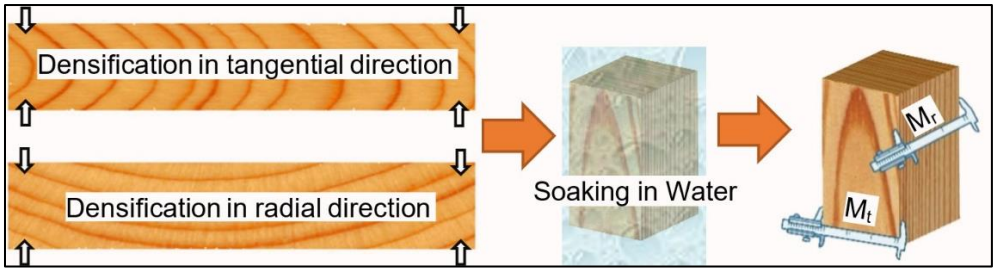

Fig. 4. Preparing and testing of samples; (M_t: measuring of samples densificated in tangential direction; M_r: Measuring of samples densificated in radial direction)

The swelling ratio in the compression direction (radial and tangential) was calculated according to Eq. 2,

$$\alpha_k = \left(\frac{L_R - L_0}{L_0} \right) \times 100 \quad (2)$$

where α_k is the swelling ratio of the compression (%), L_0 is the fully dried dimensions (mm), and L_R is the swollen dimension (mm).

Statistical analysis

The SPSS 22 statistical package program (IBM Corp., Armonk, NY) was used to evaluate the data. Multivariate analysis of variance (ANOVA) tests determined the effects of the wood type, sectional direction, surface process, densification factors, and the interactions of these factors with the density and swelling values at a significance level of 0.05. Comparisons were made using Duncan's multiple range test (DMRT) and least significant difference (LSD) critical values, and the factors causing the differences were examined.

RESULTS AND DISCUSSION

Fully Dried Density

The arithmetic means were obtained to determine the effect of the TVM densification process on the fully dried density values in terms of the wood type, sectional direction, surface process, and densification factors. Multiple variance analysis (ANOVA) was performed to determine which factor caused the difference, and the results are shown in Table 1.

Table 1. Results of the ANOVA of the Fully Dried Density Values

Factors	Degrees of Freedom	Sum of Squares	Mean Square	F Value	Level of Significance ($p \leq 0.05$)
Wood Type (A)	1	0.009	0.009	19.358	0.000*
Sectional Direction (B)	1	0.113	0.113	241.712	0.000*
Surface Process (C)	2	0.018	0.009	18.726	0.000*
Densification (D)	27	0.662	0.025	52.250	0.000*
Interaction (AB)	1	0.022	0.022	46.535	0.000*
Interaction (AC)	2	0.210	0.010	22.087	0.000*
Interaction (AD)	27	0.027	0.001	2.154	0.001*
Interaction (BC)	2	0.003	0.002	3.234	0.040*
Interaction (BD)	27	0.021	0.001	1.619	0.023*
Interaction (CD)	54	0.018	0.000	0.699	0.952
Interaction (ABC)	2	0.001	0.001	1.433	0.239
Interaction (ABD)	27	0.025	0.001	1.985	0.002*
Interaction (ACD)	54	0.018	0.000	0.693	0.956
Interaction (BCD)	54	0.025	0.000	0.982	0.513
Interaction (ABCD)	54	0.020	0.000	0.792	0.861
Error	1680	0.789	0.000	-	-
Total	2016	378.447	-	-	-
Note: *Significant at 95% confidence level					

According to the ANOVA results, the CD, ABC, ACD, BCD, and ABCD interactions were insignificant and had no effect on fully dried density value. On the other hand, the other factors and interactions were significant with respect to the fully dried density values (*p*-value was less than or equal to 0.05). Table 2 shows Duncan's multiple range test (DMRT) performed for the wood type, sectional direction, surface process, and densification factors using the LSD critical value.

Table 2. DMRT Comparison Results for the Wood Type, Sectional Direction, Surface Process, and Densification Factors (g/cm^3)

Wood Type	$\bar{x}$	HG
Uludağ fir	0.434	A*
Black poplar	0.430	B
LSD ± 0.001		
Sectional Direction	$\bar{x}$	HG
Radial	0.425	B
Tangential	0.440	A*
LSD ± 0.001		
Surface Process	$\bar{x}$	HG
Natural	0.431	B
Aniline	0.430	C
Wood preservative	0.436	A*
LSD ± 0.001		
Densification	$\bar{x}$	HG
Control	0.386	O
100 °C-0.6 MPa-20 s	0.396	N
100 °C-0.6 MPa-60 s	0.414	M
100 °C-0.6 MPa-100 s	0.429	GHIJ
100 °C-1.0 MPa-20 s	0.416	LM
100 °C-1.0 MPa-60 s	0.426	IJK
100 °C-1.0 MPa-100 s	0.435	EFGH
100 °C-1.4 MPa-20 s	0.429	GHIJ
100 °C-1.4 MPa-60 s	0.439	EF
100 °C-1.4 MPa-100 s	0.450	CD
120 °C-0.6 MPa-20 s	0.415	LM
120 °C-0.6 MPa-60 s	0.427	HIJ
120 °C-0.6 MPa-100 s	0.434	FGHI
120 °C-1.0 MPa-20 s	0.422	JKL
120 °C-1.0 MPa-60 s	0.436	EFG
120 °C-1.0 MPa-100 s	0.447	D
120 °C-1.4 MPa-20 s	0.436	EFG
120 °C-1.4 MPa-60 s	0.450	CD
120 °C-1.4 MPa-100 s	0.464	AB
140 °C-0.6 MPa-20 s	0.419	KLM
140 °C-0.6 MPa-60 s	0.427	IJ
140 °C-0.6 MPa-100 s	0.429	GHIJ
140 °C-1.0 MPa-20 s	0.424	JK
140 °C-1.0 MPa-60 s	0.436	EFG
140 °C-1.0 MPa-100 s	0.448	D
140 °C-1.4 MPa-20 s	0.442	DE
140 °C-1.4 MPa-60 s	0.457	BC
140 °C-1.4 MPa-100 s	0.470	A*
LSD ± 0.003		
Note: $\bar{x}$ = Arithmetic mean; HG = homogeneity group; and * = the highest fully dried density		

According to Table 2, the fully dried density value was highest in fir samples (0.434 g/cm^3) and lowest in the poplar samples (0.43 g/cm^3) at the wood type level. It was highest in the tangential direction (0.44 g/cm^3) and lowest in the radial direction (0.425 g/cm^3) at the sectional direction level. It was highest in the wood preservative applied samples (0.436 g/cm^3) and lowest in the aniline dye applied samples (0.43 g/cm^3) at the surface process level. With respect to densification level, it was highest in the samples where TVM densification was applied at 140 °C, 1.4 MPa, and 100 s (0.47 g/cm^3), while lowest in samples without densification (control) (0.386 g/cm^3).

Regarding the wood type factor, higher fully dried density values were obtained in the fir samples compared to the poplar samples. After undergoing the TVM densification process, the density increased up to 18.5% in fir samples and 25.5% in poplar samples compared to the control samples. The higher density increase in poplar samples may have resulted from the low density, diffuse-porous, and coarse-textured structure of this material. Thus, it was more appropriate for densification with compression. Previous studies on the compressibility of wood indicated that compressibility is dependent on the anatomical properties of the wood material, *e.g.*, density, late wood ratio, cell wall volume, and the compression direction (Kutnar and Šernek 2007). In addition, it was stated that the density increase obtained *via* compression was dependent on the spring-back effect, densification method, and the amount of compression, as well as the properties of wood. (Rautkari 2012; Pelit *et al*. 2015). In different studies, it has been reported that as the compression amount of wood increases, the density increase becomes more evident (Blomberg 2006; Rautkari *et al.* 2010; Laine 2014). In this respect, the present study is compatible with previous studies.

With respect to the sectional direction factor, higher fully dried density values were obtained in the tangential direction compared to the radial direction. After undergoing the TVM densification process, the density increased up to 23% in the radial direction and 20% in the tangential direction when compared to the control samples. In previous studies, it has been indicated that different results are obtained from the radial and tangential compression of wood due to its anisotropic structure. In addition, it is reported that radial direction samples can be less densified due to the higher rate of late wood, which can be less compressed due to its low porous structure (Blomberg *et al.* 2005; Marttila *et al.* 2016).

The highest fully dried density in regard to the surface process factor was obtained in the samples treated with wood preservative. After undergoing the TVM densification process, the fully dried density increased up to 24.3% in samples treated with wood preservative, 22.45% in untreated (but densified) samples, and 21.4% in samples treated with aniline dye compared to the undensified and untreated control samples. Previous studies stated that oil-based impregnates fill the radial rays and tracheid lumens, and the amount of oil early wood can absorb is greater than late wood due to its highly porous structure. However, it was stated that with an increase in weight, higher oil intake was observed in late wood (Olsson *et al*. 2001; Tomak 2011). It was also reported that there is a positive correlation between density and the amount of oil absorbed by the wood, which is more evident in early wood than in late wood (Ulvcrona *et al*. 2006; Tomak 2011).

At the densification factor level, an increase ranging from 15.4% to 38% was found in the fully dried density values compared to the control samples. The highest fully dried density values were obtained from samples under the following conditions: high temperatures (140 °C), high pressure (1.4 MPa), and longer compression times (100 s). In previous studies, it was emphasized that as the compression ratio increases, the density increases; this increase depends on the characteristics of the wood, the amount of

compression, and the densification method (Blomberg *et al.* 2005; Gong and Lamason 2007; Ünsal and Candan 2008; Rautkari 2012; Rautkari *et al.* 2013; Pelit et *al.* 2015; Budakçı *et al.* 2016). Therefore, the present study is compatible with previous studies.

The DMRT comparison and interaction of the results performed at the level of wood type, sectional direction, surface process, and densification factors are shown in Figs. 5 and 6, in order to illustrate the results of single comparisons together.

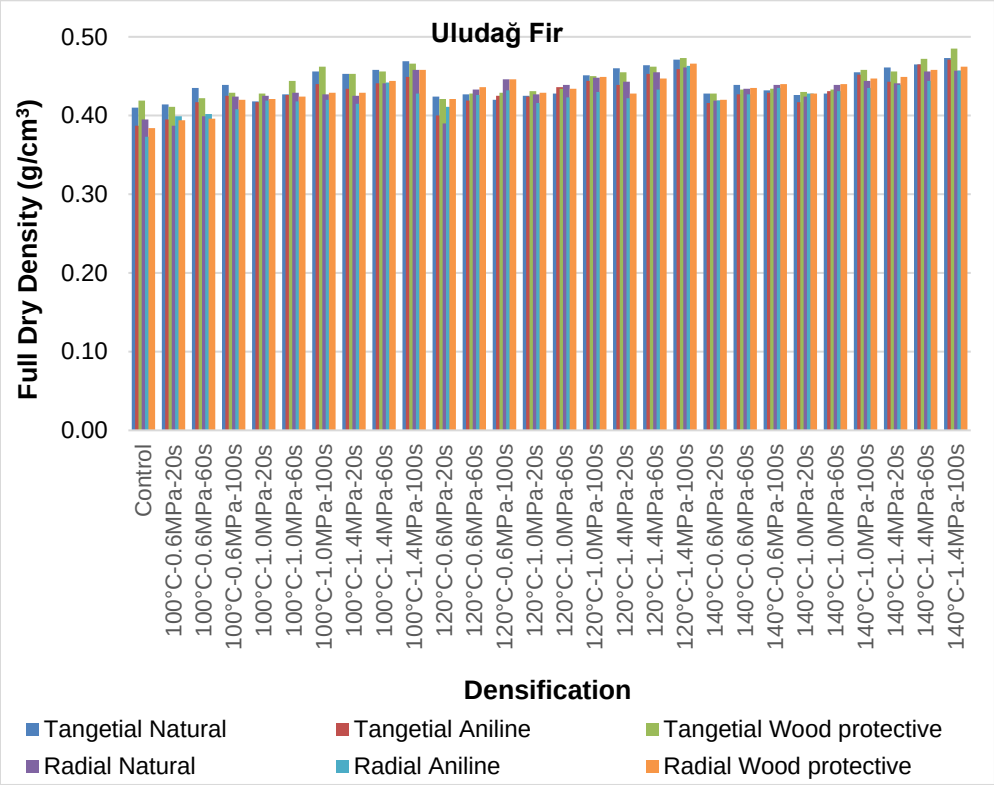

Fig 5. The DMRT comparison results of the fully dried density values for Uludağ fir at the wood type, sectional direction, surface process, and densification interaction levels (g/cm^3)

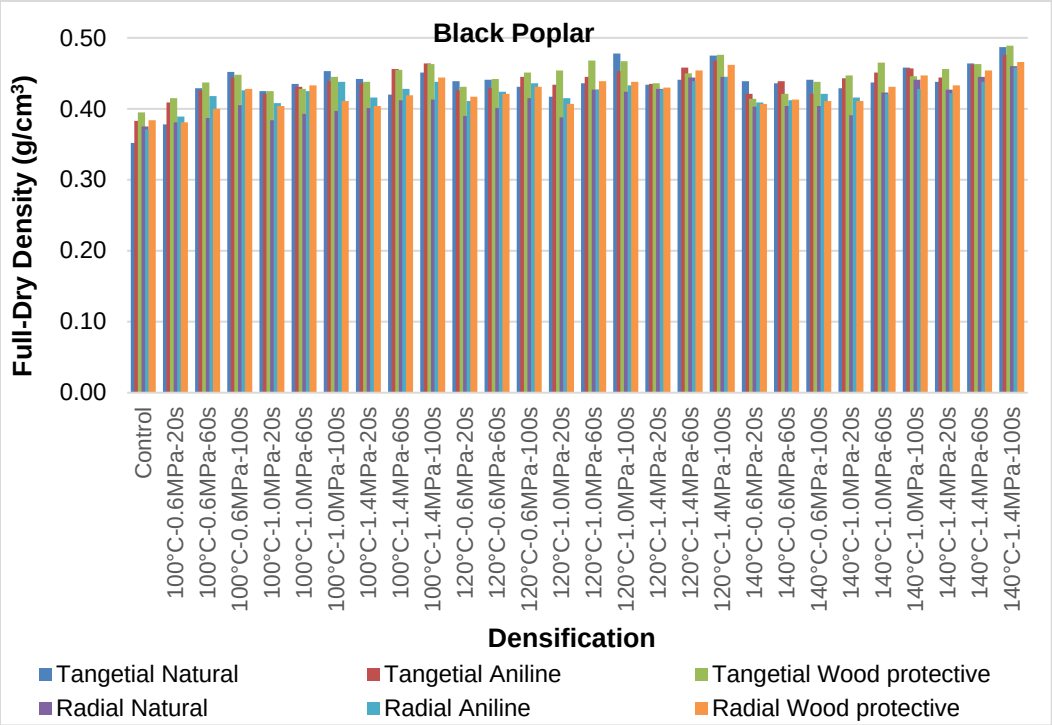

Fig. 6. The DMRT comparison results of the fully dried density values for black poplar at the wood type, sectional direction, surface process, and densification interaction levels (g/cm^3)

According to Figs. 5 and 6, the highest fully dried density value (0.489 g/cm^3) was found in the tangential direction poplar samples that were treated with wood preservative and underwent TVM densification at 1.4 MPa, 140 °C, and a duration of 100 s. The lowest value (0.352 g/cm^3) was found in the untreated and undensified tangential direction black poplar samples.

Radial and Tangential Swelling

The arithmetic means obtained to determine the effect of the TVM densification process on the swelling ratio in the radial and tangential direction were different according to wood type, sectional direction, surface process, and densification factors. An ANOVA test was performed to determine which factor caused the difference, and the results are shown in Table 3.

Table 3. ANOVA Results of Swelling in the Radial and Tangential Direction

Factors	Degrees of Freedom	Sum of Squares	Mean Square	F Value	Level of Significance ($p \leq 0.05$)
Wood Type (A)	1	241.175	241.175	448.320	0.000*
Sectional Direction (B)	1	8653.379	8653.379	16085.767	0.000*
Surface Process (C)	2	166.123	83.061	154.403	0.000*
Densification (D)	27	3747.295	138.789	257.994	0.000*
Interaction (AB)	1	168.776	168.776	313.738	0.000*
Interaction (AC)	2	18.792	9.396	17.466	0.000*
Interaction (AD)	27	322.201	11.933	22.183	0.000*
Interaction (BC)	2	47.531	23.765	44.177	0.000*
Interaction (BD)	27	736.749	27.287	50.724	0.000*
Interaction (CD)	54	646.149	11.966	22.243	0.000*
Interaction (ABC)	2	35.671	17.835	33.154	0.000*
Interaction (ABD)	27	215.587	7.985	14.843	0.000*
Interaction (ACD)	54	324.994	6.018	11.188	0.000*
Interaction (BCD)	54	370.046	6.853	12.738	0.000*
Interaction (ABCD)	54	419.065	7.760	14.426	0.000*
Error	1680	903.760	0.538		
Total	2016	131463.31			
Note: *Significant at 95% confidence level					

According to the results of the ANOVA, the wood type, sectional direction, surface process, and densification factors and their mutual interactions were significant (*p*-value was less than or equal to 0.05) with respect to the swelling ratio in the radial and tangential direction. Table 4 shows the DMRT comparison performed at the levels of wood type, sectional direction, surface process, and densification factors using the LSD critical value.

According to Table 4, the swelling ratio was the highest in the fir wood samples (7.88%) and the lowest in the poplar wood samples (7.189%) at the wood type level; it was highest in the tangential direction (9.6%) and lowest in the radial direction (5.463%) at the sectional direction level; it was highest in the untreated (control) samples (7.914%) and lowest in the wood preservative applied samples (7.219%) at the surface process level; and it was highest in the wood preservative-treated samples that underwent TVM densification at 1.4 MPa, 140 °C, and for 100 s (10.14% and 10.104%), while lowest in samples without densification (control) (4.81%) at the densification level.

Table 4. DMRT Comparison Results for the Wood Type, Sectional Direction, Surface Process, and Densification Factors (%)

Wood Type	$\bar{x}$	HG
Uludağ Fir.	7.880	A*
Black poplar	7.189	B
LSD ± 0.023		
Sectional Direction	$\bar{x}$	HG
Radial	5.463	B
Tangential	9.606	A*
LSD ± 0.023		
Surface Process	$\bar{x}$	HG
Natural	7.914	A*
Aniline	7.471	B
Wood preservative	7.219	C
LSD ± 0.028		
Densification	$\bar{x}$	HG
Control	4.810	S
100 °C-0.6 MPa-20s	5.123	R
100 °C-0.6 MPa-60s	5.633	P
100 °C-0.6 MPa-100s	6.644	N
100 °C-1.0 MPa-20s	6.382	O
100 °C-1.0 MPa-60s	7.076	KLM
100 °C-1.0 MPa-100s	7.475	HI
100 °C-1.4 MPa-20s	7.356	HIJ
100 °C-1.4 MPa-60s	7.573	GH
100 °C-1.4 MPa-100s	9.049	CD
120 °C-0.6 MPa-20s	5.864	P
120 °C-0.6 MPa-60s	6.834	MN
120 °C-0.6 MPa-100s	7.109	JKL
120 °C-1.0 MPa-20s	7.029	LM
120 °C-1.0 MPa-60s	7.303	HIJK
120 °C 1.0 MPa-100s	8.352	F
120 °C-1.4 MPa-20s	8.664	E
120 °C-1.4 MPa-60s	9.277	BC
120 °C-1.4 MPa-100s	10.104	A*
140 °C-0.6 MPa-20s	6.319	O
140 °C-0.6 MPa-60s	7.381	HI
140 °C-0.6 MPa-100s	7.449	HI
140 °C-1.0 MPa-20s	7.215	IJKL
140 °C-1.0 MPa-60s	7.779	G
140 °C-1.0 MPa-100s	8.971	D
140 °C-1.4 MPa-20s	8.707	E
140 °C-1.4 MPa-60s	9.346	B
140 °C-1.4 MPa-100s	10.140	A*
LSD ± 0.086		

Note: x̄ = Arithmetic mean; HG = homogeneity group; and * = the highest fully dried density

With respect to the wood type factor, a higher swelling ratio was obtained in the fir samples compared to the poplar samples. It can be argued that the different initial densities and structural differences (void volume, chemical composition, *etc*.) of the wood materials influenced the results. It has been stated by previous studies (Pelit *et al*. 2014, 2016) that in materials with a large cell wall volume but a lower void volume, internal stresses occur due to the effects of the temperature and pressure during the compression process, and this situation causes an increase in spring-back and water intake capability. Previous studies have reported that the density of wood can be increased *via* densification processes, but

that condensed wood tends to revert to its initial dimensions when exposed to high levels of moisture or water (Seborg *et al.* 1956; Kollmann *et al*. 1975; Morsing 2000; Blomberg *et al*. 2006). The reason for this situation is explained by the fact that the cell wall expands due to the increased water/moisture. These results are consistent with previous findings.

Regarding the sectional direction factor, a higher swelling ratio was obtained in the tangential direction compared to the radial one. Swelling rates up to 140.91% in the tangential direction and 75.75% in the radial direction were obtained from TVM densified samples compared to the control samples. Different studies have indicated that tangential swelling is always greater than radial, and longitudinal swelling is considered negligible (Kollmann *et al*. 1975; Usta and Güray 2000). However, the reasons for the difference between radial and tangential swelling are not clear. This is partly attributed to the presence of rays, which (due to their radial orientation) exercise a hindering influence on the radial swelling. When the fibers are joined to the rays, they anchor the fibers in place; therefore, the rays do not hinder but increase tangential swelling. Another possible reason could be the different swelling abilities of early and latewood.

Higher swelling ratios were obtained in the control (untreated) samples according to the surface process factor. After undergoing the TVM densification process, the swelling extent was a high as 89.3% in wood preservative-treated samples, 152% in untreated samples, and 112.5% in aniline dye applied samples, when compared to the (natural) control samples. It can be concluded that the aniline dye and oily wood preservative used for the surface treatments gave the wood hydrophobic properties, and therefore it significantly reduced the total water intake. It has been reported in past studies that oily compounds reduce the water intake by forming a mechanical barrier with no chemical bonding in the structure of the wood (Panov *et al.* 2010), which provides water repellency by settling in the tracheid lumens and rays (Ulvcrona 2006). The oil that fills the cell lumens is primarily stored on the outer surface of the wood and partially inside the wood, so the surface of the wood shows hydrophobic properties. Since the water enters the inner parts through the pores on the surface of the wood *via* the capillary effect, the amount of water intake decreases (Koski 2008).

At the densification factor level, the swelling rate ranged from 73.2% to 242.6% when compared to the control samples. The highest swelling ratio was obtained from the samples that underwent TVM at the following conditions: a high temperature (140 °C), high pressure (1.4 MPa), and a longer compression time (100 s). It was determined that there was a strong positive linear relationship between compression and the swelling ratio. In similar studies, it was demonstrated that the compression parameters remarkably affect the dimensional stability of the samples and that greater swelling occurs in the samples densified with a higher compression level (Lamason and Gong 2007; Ünsal *et al.* 2011; Cai *et al*. 2012; Pelit *et al.* 2014; Budakçı *et al*. 2015; Pelit *et al*. 2016). It was also stated by Cai *et al.* (2012) that the compression time and temperature are not important in terms of dimensional stability.

The DMRT comparison results performed at the levels of wood type, sectional direction, surface process, and densification factors interaction are shown in Figs. 7 and 8 in order to illustrate the results of single comparisons together.

According to Figs. 7 and 8, the highest swelling ratio (20.7%) was found in the tangential direction poplar samples treated with wood preservative and underwent TVM densification at 1.4 MPa, 140 °C, and a duration of 100 s. The lowest value (3.14%) was found in the untreated and undensified (control) radial direction poplar samples.

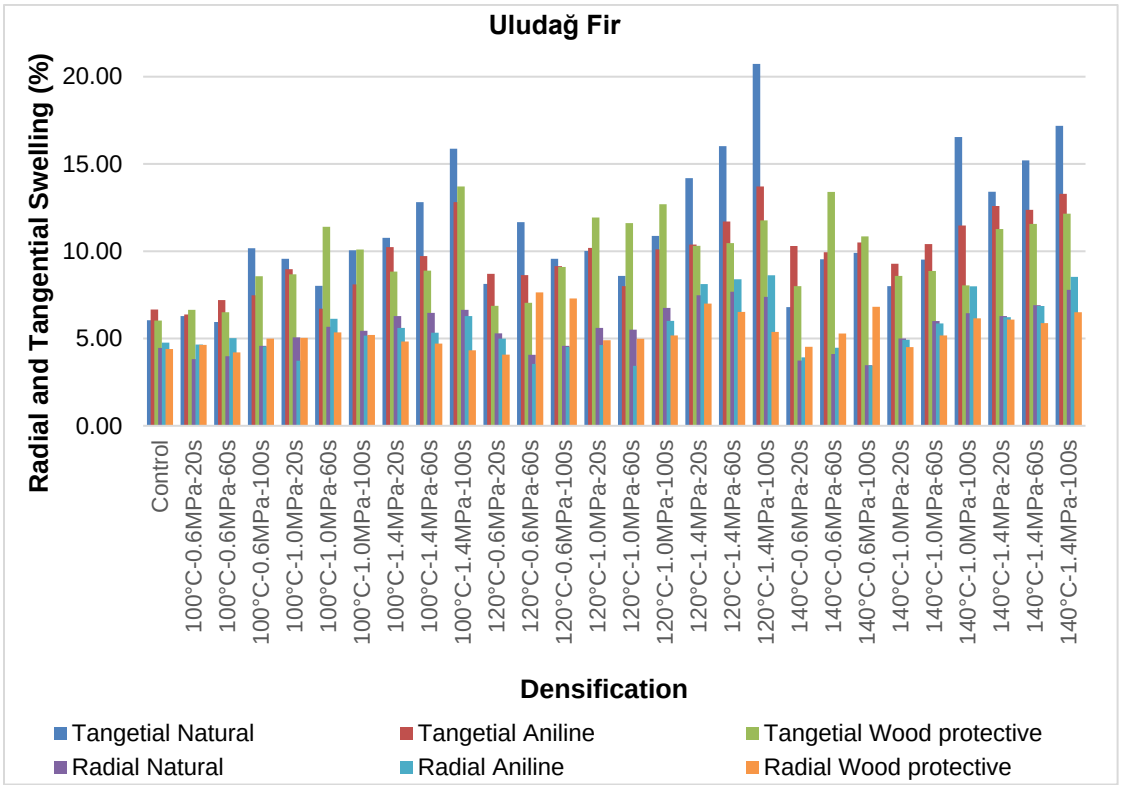

Fig. 7. The DMRT comparison results of the radial and tangential swelling values for Uludağ fir at the wood type, sectional direction, surface process, and densification interaction levels (%)

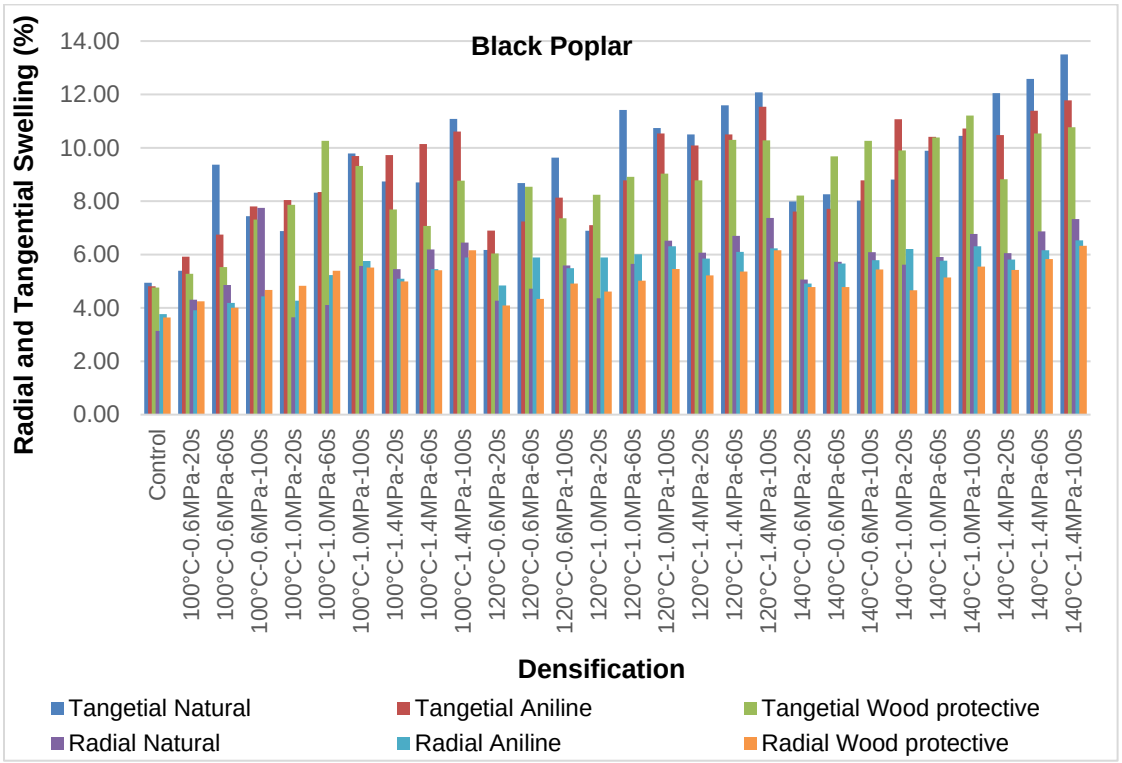

Fig. 8. The DMRT comparison results of the radial and tangential swelling values for black poplar at the wood type, sectional direction, surface process, and densification interaction levels (%)

CONCLUSIONS

1. Thermo-Vibro-Mechanic® (TVM) densification noticeably increased the fully dried density value of the Uludağ fir samples compared to the undensified control samples.
2. The fully dried density values were found to be higher in the fir samples compared to the poplar samples. They were found to be higher in the tangentially compressed samples compared to the radially compressed samples. In addition, they were found to be higher in the preservative-treated samples compared to the control and aniline dye treated ones.
3. The highest fully dried density values were obtained in samples densified for the longest time (100 s) at the highest temperature (140 °C), and at the highest pressure (1.4 MPa).
4. TVM densification remarkably increased the swelling ratio in both directions compared to the control samples.
5. Swelling in the radial and tangential directions were higher in the fir samples than in the poplar samples; were higher in the samples compressed in the tangential direction than the samples compressed in the radial direction; and were higher in the control samples than in the wood preservative and aniline dye applied samples.
6. The highest swelling rate was obtained in the samples densified for the longest time (100 s) at the highest temperature (140 °C), and at the highest pressure (1.4 MPa).
7. In general, it can be said that the density and swelling values increased depending on the TVM densification parameters, and higher values were found as the compression ratio and application time increased.

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