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The effect of thermo-mechanical densification process on the physical properties of wood material

Termo–mekanik yoğunlaştırma işleminin ahşap malzemenin fiziksel özellikleri üzerine etkisi

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Abstract
It can be made into high strength, and valuable products by compacting low density, and low commercial value wood species. In this study, black pine *(Pinus nigra)* and Uludağ fir *(Abies nordmanniana* subsp. *bornmulleriana)* tree species were densified by using Thermo-mechanical (TM) method, which is an environmental modification method, at 140 ºC and two different ratios of 25% and 50% (in the radial direction). Compression ratio in air-dry moisture, spring-back ratio after densification, and physical properties of air-dry densities were determined. The obtained data were subjected to statistical analysis in the MSTAT-C program. According to the results, wood type, densification type, and all their interactions were found to be effective on the compression ratio, and spring-back ratio in air dry moisture. The compression ratio in air-dried moisture was lower in Uludağ fir (Uludağ fir: 0.40 gr/cm³, black pine: 0.49 gr/cm³) compared to black pine due to the spring-back effect. While the volumetric recovery (spring-back) rates were 15.44% in Uludağ fir, it was determined as 19.40% in black pine. After the condensation process, the air-dry density value increase was lower in black pine compared to Uludağ fir, and it was determined as 35.94% in Uludağ fir and 34.53% in Black Pine.

Özet
Düşük yoğunluklu ve ticari değeri zayıf olan ağaç türleri sıkıştırmak suretiyle, yüksek dayanımlı ve değerli ürünler haline getirilebilir. Bu amaçla yapılan çalışmada, karaçam *(Pinus nigra)* ve Uludağ göknarı *(Abies nordmanniana* subsp. *bornmulleriana)* ağaç türleri çevreci bir modifikasyon yöntemi olan Termo-mekanik (TM) yöntemle 140 ºC sıcaklık ve %25 ve %50 iki farklı oranda (radyal yönde) sıkıştırılarak yoğunlaştırılmıştır. Hava kurusu rutubetteki sıkıştırma oranı, yoğunlaştırma sonrası geri esneme (yaylanma) oranı ve hava kurusu yoğunluklara ait fiziksel özellikler belirlenmiştir. Elde edilen veriler, MSTAT-C programında istatistiksel analize tabi tutulmuştur. Sonuçlara göre ağaç türü, yoğunlaştırma şekli ve bunların tüm karşılıklı etkileşimleri hava kurusu rutubetteki sıkıştırma oranı üzerinde ve geri esneme oranı üzerinde etkili bulunmuştur. Hava kurusu rutubetteki sıkıştırma oranı, geri esneme etkisine bağlı olarak karaçama göre Uludağ göknarında daha düşük (Uludağ göknarı: 0.40 gr/cm³, karaçam: 0.49 gr/cm³) elde edilmiştir. Hacimsel geri kazanım (spring-back) oranları ortalama olarak Uludağ göknarında %15.44 iken karaçamda %19.40 olarak tespit edilmiştir. Yoğunlaştırma işlemi sonrası hava kurusu yoğunluk değer artışı, Uludağ göknarına göre karaçamda daha düşük yani; Uludağ göknarında %35.94 ve karaçamda %34.53 seviyesinde belirlenmiştir.

INTRODUCTION

Wood material has become an industrial product whose usage area has become quite widespread with the technological advances in recent years. The increase in the need of the sector causes the growing forest assets to decrease day by day. In this case, the modification of wood species with low resistance properties is imperative. In the woodworking industry, the desire for durable wood material, the growing value, and the ecology consciousness caused by the shrinking forest stand have become a necessity to expand the usage area in the industry by increasing the strength properties of loose-textured wood types (densification modification) (Pelit 2014).

"Wood Modification Methods" are used to eliminate some negative properties of wood material (Rautkari et al. 2009, Şenol and Budakçı 2016, Şenol 2018, Tosun 2021). The term “wood modification” is defined as changing or improving the negative properties of wood (Şenol and Budakçı 2016, Sandberg et al. 2017).

High-density wood is needed in carrier systems, and areas where abrasion resistance is important. Species with low density, and no commercial value can be treated with densification processes, increasing their strength, and making them valuable products. Even wood types that are in the hard class with high density can be partially compressed and made denser to improve their physical strength (Blomberg and Person

2004, Blomberg et al. 2005, Kutnar and Šernek 2007). Kadivar et al. (2019) stated that the Thermo-Mechanical (TM) condensation technique is one of the methods considered environmentally friendly (Kadivar et al. 2019).

The idea of compressing wood material by heating, and applying pressure has been known for more than a century. In addition, the process of compacting wood in the radial direction has been available in the literature since 1886 (Kollmann and Côté 1968, Heger et al. 2004).

Wood material is insufficient in load-bearing wooden structures where high durability, and resistance are required. Hardwoods with higher density are needed to make up for this deficiency. This situation rivals other materials used in buildings (Homan et al. 2000, Blomberg and Persson 2004, Kutnar and Šernek 2007, Laine et al. 2013, Laine 2014, Pelit et al. 2014).

As solid wood is compressed, it will decrease in volume, but its strength will increase (Ulker et al. 2012). But as a disadvantage, spring-back will ocur (Tosun and Sofuoğlu 2021). Thus, the wettability of wood with increasing specific gravity decreases and its mechanical properties increase (Arruda and Menezzi 2013). In addition, it is thought that the decrease in the density, and resistivity of wood materials as a result of heat treatment (ThermoWood) can be compensated by thermo-mechanical densification (TMD) (Pelit et al. 2015). After the compression process, many mechanical, and physical properties of wood material can change (Sofuoglu 2022). Since thermo-mechanical densification also includes heat treatment, heat treatment applications in wood increase dimensional stability by reducing hygroscopicity (Perçin et al. 2016).

The disadvantage of compaction densification is that wood reverts to its precompaction size when immersed in water or exposed to high relative humidity (Seborg et al. 1956, Kollmann et al. 1975, Kultikova 1999, Morsing 2000, Blomberg et al. 2006, Gong and Lamason 2007, Pelit 2014, Pelit et al. 2014).

In this study; it was aimed to determine the effects of densification on the physical properties of Black pine *(Pinus nigra)* and Uludağ fir *(Abies nordmanniana* subsp. *bornmulleriana),* which are coniferous trees with partially low density.

MATERIAL AND METHOD

Material

Wood Material

In this study, partially low-density Black pine (*Pinus nigra*) and Uludağ fir (*Abies nordmanniana* subsp. *bornmulleriana*), which are widely used in the woodworking industry in Türkiye, were preferred. These wood materials are produced by “Akınlar Kereste Industry Trade”. It was obtained as lath from timber that was not subjected to technical drying by random selection method from the company. Care has been taken to ensure that the wood material is free of rot, knots, gaps, and smooth fibers.

Preparation of Experimental Samples

The test specimens prepared according to ISO 3129 were prepared from sapwood, which was not damaged by insects, and fungi, free of knots, cracks and arcs, free of discoloration, smooth fiber structure, annual rings parallel to the surface (tangential cross-section) (ISO 3129 2019).

Afterwards, these timbers were dried in an automatically managed drying oven to an average of 12% moisture. In order to be used in the related tests, sufficient amounts of test samples were cut in the draft dimensions specified in Table 1 for the control groups and the groups to be condensed. In order to obtain the targeted compression thickness (10 mm), and compression ratios (25%, and 50%), the test samples to be densified were brought to two different thicknesses (13.33 mm, and 20 mm) (Table 1).

Table 1. Precompression measurements of the test samples to be used in the physical properties determination tests

Compression ratio	Dimensions (mm)		
	Length longitudinal direction)	Width (tangent direction)	Thickness (radial direction)
Control	500	100	10.0
25%	500	100	13.33
50%	500	100	20

Before the densification processes, the test samples were kept in the air-conditioning cabinet with a temperature of 20±2 °C, and a relative humidity of 65±5% until they reached the constant weight. In order to prevent humidity changes that may occur after conditioning, the test samples were kept in the air conditioning cabinet until densification.

Thermo-Mechanical Densification of Test Samples

The black pine and Uludağ fir samples, which were cut to the draft dimensions, were compressed, and condensed in the open system by thermo-mechanical (TM) method, by means of a specially designed resistance hydraulic press with a table size of 60x60 cm, which can be controlled by temperature and pressure (100 tons-250 atm) (Figure 1).

Figure 1. Hydraulic press used in densification processes

The densification process was carried out at 140±5 °C (When the densification process started, a temperature of 140 °C was preferred, which is thought to be the most ideal for breaking/breaking in wood tissue fiber structures. Lives below this temperature may have filters. Mechanical properties and surface properties may be adversely affected by exposing this temperature to high heat on wood material) by creating two different variations at 25% and 50% compression ratios. Densification variations are given in Table 2.

Table 2. Compression variations of test samples to be used in determination of physical properties tests

Densification		
Press temperature	Compression ratio	Duration
140 °C	25%	Heating + 15 Min.
	50%	Heating + 15 Min.

The test specimens placed on the press table were first kept under a slight pressure so that both surfaces were in contact with the press table, and were kept in this position for a while, controlled by a digital heat meter, until the internal temperature of the test specimens reached the temperature of the press tables (140 °C). In order to achieve the targeted compression ratios, 10 mm thick metal stopper profiles are placed on the press table at regular intervals.

Then, radial compression of the samples was carried out with automatic control at a loading speed of 60 mm/minute. The compressed test samples were kept under pressure for 15 minutes and at the end of this period, the samples were taken from the press and allowed to cool down to room temperature under an average pressure of 5 kg/cm^2 in order to minimize the spring-back effect.

Figure 2. Internal temperature of test samples during densification processes

Dimensioning of Test Samples

The control, and condensed test samples to be used in determining the physical properties were measured using band saw, and planer thickness machines in accordance with the prescribed tests and relevant standards. Dimensions and sample numbers are given in Table 3.

Before the tests, the test samples were conditioned according to TS ISO 13061-1 (TS ISO 13061-1 2021) at 20±2 ˚C temperature and 65±5% relative humidity conditions in the air conditioning cabinet until they reached a constant mass. In order to prevent humidity changes after conditioning, the test samples were kept in plastic bags until the test.

Table 3. For tests of physical properties, test sample design

Wood type	Compression ratio (%)	Dimensions (mm)	Total (number)
Black pine	0 (Control)	100×100×10	10
	25	100×10×13.33	10
	50	100×100×20	10
Uludağ Fir	0 (Control)	100×100×10	10
	25	100×10×13.33	10
	50	100×100×20	10
		Total	**60**

Method

Determination of Compression Ratio in Air Dry Moisture After Densification

The test samples were theoretically compressed in two different ratios (25% and 50%) in a hot press. However, after removing the press pressure, there was a momentary spring-back caused by the release of internal stresses in the test samples due to compression. In addition, moisture losses in the test samples due to the effect of the temperature in the compression process also caused a spring-back after the samples were conditioned at 20±2 °C temperature, and 65±5% relative humidity. As a result, changes (decreases) occurred in the theoretical compression ratios applied during the pressing phase.

Before, and after compression, the test samples were kept in the air conditioning cabinet at 35±2 °C and 20±2% relative humidity until their masses were unchanged. In this case, their thickness was determined by measuring with a digital caliper (with an accuracy of ±0.01 mm), and the compression ratios obtained in air dry moisture after densification were calculated according to the formula below (Navi and Girardet 2000, Welzbacher et al. 2008, Dubey 2010).

CO= ((T1-T2)/T1) ×100

Where;

CO = Compression ratio in air dry moisture after densification (%)

T1 = Thickness in air dry moisture before compression (mm)

T2 = Thickness in air dry moisture after compression (mm)

Determination of Spring-Back Ratio

The thickness of the test samples under pressure (metal stopper lath thickness) during the pressing phase and the post conditioning thickness at 20±2 °C temperature, and 65±5% relative humidity conditions after pressing were determined by measuring with a digital caliper (±0.01 mm precision). Spring-back rates were calculated according to the following equation.

SPR= ((T4-T3)/T3) ×100

Where;

SPR = Spring-back rate (%)

T3 = Thickness under pressure (mm) (metal stopper strip thickness)

T4 = Thickness in air dry moisture after compression (mm)

Determination of Air-Dry Density

Air dry density measurements were made in accordance with the principles of TS ISO 13061-2 (TS ISO 13061-2 2021). The prepared test samples were kept in the air conditioning cabinet at 20±2 °C and 65±5% relative humidity until they reached the constant mass. The masses (M_{12}) of the samples in this condition were weighed on an analytical balance with an accuracy of ±0.01 g, their dimensions (length, width, thickness) were measured with a digital caliper (with an accuracy of ±0.01 mm), and their volumes (V_{12}) were determined (Figure 3). Using these determined values, air dry densities were calculated according to "Equation 1".

$$\delta_{12}=\mathrm{M}_{12}/\mathrm{V}_{12} \quad (1)$$

Here;

δ_{12}= Air dry density (g/cm³)

M_{12} = Air dry mass (g)

V_{12} = Air dry volume (cm³)

Evaluation of Data

The test results were analysed with a computerized MSTAT-C statistical program that included the "analysis of variance" ANOVA" and the "DUNCAN" test applied at 95% confidence level. Statistical evaluations were made on homogeneity groups (HG) according to the least significant difference (LSD) critical value, where different letters reflect statistical significance.

Figure 3. Conditioning of samples at 20±2 °C temperature and 65±5% relative humidity and measurement of air-dry densities

RESULTS

The data, and analyses of the air-dry moisture compression ratio, the spring-back rate after densification, and the air-dry densities of black pine, and Uludağ fir densified by the thermo-mechanical (TM) method at 140 and two different ratios are given below.

Compression Ratio in Air-Dry Moisture After Densification

The post compression thickness and compression ratio values are given in Table 4 depending on the wood type, densification type, and thickness.

The analysis of multiple variances is given in Table 5 in order to determine whether the wood type, and densification shape, and their interactions have an effect on the compression ratio in air-dry moisture.

According to the results of multivariance analysis, wood type, densification type and all their interactions were found to be effective on the compression ratio in air-dry moisture ($P \leq 0.05$).

Effect of Thickness on Compression Ratio

The homogeneity group comparisons made to determine the differences between the thickness and the compression ratio in air-dry moisture after densification are given in Table 6.

According to the Table 7; while the average thickness before compression was 16.665 mm, it decreased to 10.32 mm after compression up to the pressing thickness (10 mm).

Effect of Wood Type and Thickness on Compression Ratio

Homogeneity group comparisons made in order to determine the differences between wood type, and thickness, and compression ratio in air-dry moisture before, and after densification are given in Table 7.

Effect of Thickness and Densification on Compression Ratio

The homogeneity group comparisons made to determine the differences between the thickness, and densification, and the compression ratio in air-dry moisture after densification are given in Table 8.

Effect of Wood Type and Densification on Compression Ratio

Homogeneity group comparisons made in order to determine the differences between wood type, and densification, and the compression ratio in air-dry moisture after densification are given in Table 9.

Table 4. Post compression thickness and compression ratio values depending on wood type, densification type and thickness

Wood Materials	Densification rate and temperature	Thickness before compression	Pressing thickness (mm)	Thickness after compression (mm)	Compression ratio (%)	St. S.
Black Pine	140 ºC- 25%	13.33	10	10.27	22.96	0.19
	140 ºC -50%	20	10	10.78	46.10	0.55
Uludağ Fir	140 ºC- 25%	13.33	10	10.10	24.23	0.07
	140 ºC -50%	20	10	10.47	47.65	0.33

Table 5. Analysis of variance on the effect of wood type, densification shape, and thickness on compression ratio

Factors	Degrees of freedom	Sum of squares	Mean square	F-value	Level of significance (P ≤ 0.05)
Wood type (A)	1	7.004	7.004	768.1240	0.0000*
Densification (B)	1	232.826	232.826	25535.6936	0.0000*
Interaction (AB)	1	7.405	7.405	812.1922	0.0000*
Thickness (C)	2	885.143	442.572	48539.9854	0.0000*
Interaction (AC)	2	15.522	7.761	851.2044	0.0000*
Interaction (BC)	2	435.015	217.507	23855.5756	0.0000*
Interaction (ABC)	2	15.096	7.548	827.8212	0.0000*
Error	108	0.985	0.009		
Total	**119**	**1898.995**			

Table 6. Homogeneity groups according to the compression ratio values in air-dry moisture according to thickness

Thickness	$\bar{x}$ (mm)	HG
Thickness before compression	16.665	A*
Pressing thickness	10	B
Thickness after compression	10.321	B
LSD: ± 0.04200		

$\bar{x}$: Arithmetic mean, HG: Homogeneous group, *: Highest compression ratio

Table 7. Homogeneity groups according to wood type and thickness, compression ratio values in air-dry moisture

Wood Materials	Thickness	$\bar{x}$ (mm)	HG
Black Pine	Thickness before compression	16.665	A*
	Pressing thickness	10	B
	Thickness after compression	10.346	B
Uludağ Fir	Thickness before compression	16.665	A*
	Pressing thickness	10	B
	Thickness after compression	10.296	B
LSD: ± 0.05940			

$\bar{x}$: Arithmetic mean, HG: Homogeneous group, *: Highest compression ratio

Table 8. Homogeneity groups according to the compression ratio values in air-dry moisture according to thickness and densification type

Thickness	Densification rate (%)	$\bar{x}$ (mm)	HG
Thickness before compression	0	13.33	B
Pressing thickness	25	10	C
Thickness after compression	25	10.185	C
Thickness before compression	0	20	A*
Pressing thickness	50	10	C
Thickness after compression	50%	10.630	C
LSD: ± 0.05940			

$\bar{x}$: Arithmetic mean, HG: Homogeneous group, *: Highest compression ratio

Table 9. Homogeneity groups according to the compression ratio values in air dry moisture according to wood type and densification type

Wood Materials	Densification rate (%)	$\bar{x}$ (mm)	HG
Black Pine	25	11.176	B
	50	13.465	A*
Uludağ Fir	25	10.196	C
	50	13.478	A*
LSD: ± 0.04850			

$\bar{x}$: Arithmetic mean, HG: Homogeneous group, *: Highest compression ratio

Effect of Wood Type, Densification and Thickness on Compression Ratio

Homogeneity group comparisons made to determine the differences between wood type, densification and thickness, and compression ratio in air-dry moisture after densification are given in Table 10.

Table 10. Homogeneity groups of wood type, densification and thickness in air-dry moisture compression ratio values

Wood Materials	Densification rate	Thickness	$\bar{x}$ (mm)	HG
Black Pine	0%	Thickness before compression	13.330	B
	25%	Pressing thickness	10	C
	25%	Thickness after compression	10.197	C
	50%	Thickness before compression	20	A
	50%	Pressing thickness	10	C
	50%	Thickness after compression	10.394	C
Uludağ Fir	0%	Thickness before compression	10.330	B
	25%	Pressing thickness	10	B
	25%	Thickness after compression	10.257	B
	50%	Thickness before compression	20	A
	50%	Pressing thickness	10	B
	50%	Thickness after compression	10.435	B
LSD: ± 0.08401				

$\bar{x}$: Arithmetic mean, HG: Homogeneous group, *: Highest compression ratio

Spring-Back Rate

The arithmetic averages of the spring-back ratio values in air-dry moisture obtained from the spring-back test samples depending on the tree species, and densification are given in Table 11.

Table 11. Arithmetic mean of spring-back rate values (%)

Wood Materials	Densification rate	$\bar{x}$ (%)	St. S.	HG
Black Pine	25%	10.75	0.75	C
	50%	28.04	1.98	A
Uludağ Fir	25%	7.08	0.5	D
	50%	23.79	1.68	B

$\bar{x}$: Arithmetic mean, St.S: Standard deviation

The analysis of multiple variances to determine whether the tree type, densification shape, thickness, and their interactions have an effect on the spring-back rate is given in Table 12. According to the results of the analysis of multiple variances, the effect of tree species and densification on the spring-back rate and their interactions were found to be significant.

The homogeneity group comparisons made to determine the differences between the spring-back values at the compression level are given in Table 13. According to the Table 13; The spring-back rate was obtained in the test samples, which were compressed at the highest 50% (28.04%), and in the test samples, which were compressed at the lowest 25% (7.08%).

Table 13. Homogeneity groups (%) belonging to spring-back ratio values at the densification level

Wood Materials	Densification rate	$\bar{x}$ (%)	HG
Black Pine	25%	10.75	C
	50%	28.04	A*
Uludağ Fir	25%	7.08	D
	50%	23.79	B
LSD: ± 0.1126			

Effect of Wood Type and Densification on Spring-Back Rate

The homogeneity group comparisons made to determine the differences between wood type, and densification and the spring-back rate in air-dry moisture after densification are given in Table 14

Table 14. Homogeneity groups according to the spring-back ratio values in air dry moisture according to wood type and densification type

Wood Materials	Densification rate and temperature	$\bar{x}$ (mm)	HG
Black Pine	140 ºC 25%	10.567	B
	140 ºC 50%	11.195	A*
Uludağ Fir	140 ºC 25%	10.359	B
	140 ºC 50%	11.402	A*
LSD: ± 0.1592			

$\bar{x}$: Arithmetic mean, HG: Homogeneity group, *: The highest spring-back rate

Table 12. Analysis of variance on the effect of wood type, densification shape and thickness on the spring-back rate

Factors	Degrees of freedom	Sum of squares	Mean square	F-value	Level of significance (P ≤ 0.05)
Wood type (A)	1	0.000	0.000	0.000	-
Densification (B)	1	13.945	13.945	216.9290	0.0000*
Interaction (AB)	1	0.861	0.861	13.3962	0.0005*
Thickness (C)	1	62.058	62.058	945.4059	0.0000*
Interaction (AC)	1	0.000	0.000	0.000	-
Interaction (BC)	1	13.945	13.945	216.9290	0.0000*
Interaction (ABC)	1	0.861	0.861	13.3962	0.0005*
Error	72	4.628	0.064		
Total	**79**	**96.297**			

*: significant relative to 0.05, Ns: It's insignificant

Effect of Thickness and Densification on Spring-Back Rate

The homogeneity group comparisons made to determine the differences between the thickness and the densification and the spring-back rate in air-dry moisture after densification are given in Table 15.

Table 15. Homogeneity groups according to the spring-back ratio values in air-dry moisture according to thickness and densification type

Thickness	Densification rate	$\overline{x}$ (mm)	HG
After press	25%	10.00	B
Air dry in moisture	25%	10.926	B
After press	50%	10.00	B
Air dry in moisture	50%	12.526	A*
LSD: ± 0.1592			

$\overline{x}$: Arithmetic mean, HG: Homogeneity group, *: The highest spring-back rate

Effect of Wood Type, Densification and Thickness on Spring-Back Rate

The homogeneity group comparisons made in order to determine the differences between wood type, densification and thickness, and the spring-back rate in air-dry moisture after densification are given in Table 16.

Table 16. Homogeneity groups of wood type, densification and thickness values of spring-back rate in air-dry moisture

Wood Materials	Densification rate	Thickness	$\overline{x}$ (mm)	HG
Black Pine	25 %	After press	10.00	C
	25 %	Air dry in moisture	11.134	B
	50 %	After press	10.00	C
	50 %	Air dry in moisture	12.389	A
Uludağ Fir	25 %	After press	10.00	B
	25 %	Air dry in moisture	10.719	B
	50 %	After press	10.00	B
	50 %	Air dry in moisture	12.804	A*
LSD: ± 0.2252				

$\overline{x}$: Arithmetic mean, HG: Homogeneity group, *: The highest spring-back rate

Air Dry Density

The arithmetic averages of the air-dry density values obtained from the test samples are given in Table 17. At tree species level, air-dried density was lower in black pine than in Uludağ fir. With the densification processes, an average density increases of 34.53% was achieved in black pine and up to 35.94% in Uludağ fir compared to control samples.

Table 17. Arithmetic averages of air-dry density values (g/cm^3)

Wood Materials	$\bar{x}$ (gr/cm^3)	St. S.	HG
Black Pine	0.49	0.02	A
Uludağ Fir	0.40	0.02	B

$\bar{x}$: Arithmetic mean, St.S: Standard deviation

DISCUSSION AND CONCLUSIONS

In this study; the determination of the effect of the thermo-mechanical densification process on the physical properties of black pine and Uludağ fir was analysed. The results obtained from the analyses, and the discussion based on these results are given below. After the densification process based on 10 mm net thickness, the compression ratio in air-dry moisture was lower in Uludağ fir than in black pine due to the spring-back effect. This may be due to the difference in the initial densities of wood materials before compaction (Uludağ fir: 0.40 gr/cm^3; black pine: 0.49 gr/cm^3). Due to the lower density, the amount of structural material is low in Uludağ fir, and the amount of voids is high. On the other hand, in black pine, the amount of structural material is higher, the amount of voids is less. In black pine, more structural material is compressed by the densification process, creating more tension in the cell walls. By removing the compression process, the higher stress will result in relatively greater volumetric recovery in black pine, resulting in a higher compression ratio in Uludağ fir. While the volumetric recovery (spring-back) rates were 15.44% in Uludağ fir, and 19.40% in black pine. The air-dry density value increase, which occurs with the conditioning of the samples under normal conditions after the densification process, is lower in black pine than in Uludağ fir, and is 35.94% in Uludağ fir and 34.53% in black pine. This is because the volumetric recovery rate after densification is higher in black pine.

Heating and/or steaming before compression have been found to reduce densified wood spring-back significantly (Inoue et al. 2008). Time and temperature affect the woodiness to a constant degree and satisfies the spring-back. According to Sadatnezhad et al. (2017) time and temperature have a constant effect on wooding and satisfies spring-back (Sadatnezhad et al. 2017).

It shows parallelism with the similar work in the literature on spring-back and special weight. Pelit et al. (2016) determined the spring-back rates of Uludağ fir, and black poplar as 10.36% and 12.73%, respectively, for which they intensified thermo-mechanical properties (25% and 50%) (Pelit et al. 2016). Pelit (2014), on the other hand, wants to spring-back, obtained high (11.33%) in Eastern beech samples, and lower (5.81%) in Scots pine samples. With the intensification processes, an estimated increase of up to 42% in Scots pine and 35% in Eastern beech was achieved compared to the control samples (Pelit 2014).

Özdemir (2020), on the other hand, found the spring-back rates of thermo-mechanically compressed poplar coatings at 50%, 75% and 100%, respectively, to be 15.16%, 21.83% and 36.84%, respectively. Arısüt (2021), condensed fir at 120, 150, 180 °C, and 20%, and 40% densities, respectively, determined the air-dry ownership weights of 0.56, 0.70, 0.52, 0.65, 0.52 and 0.66 gr/cm³ of poplar wood, 0.49, 0.63, 0.49, 0.60, 0.47 and 0.60 gr/cm³ found.

The increase in density normally increases the volumetric recovery rate. For this reason, it is necessary to consider this situation when densifying denser woods, and to choose a lower net thickness measure compared to softwoods. In Türkiye, there are relatively low-density tree species whose growing area is widespread, and usage area is limited. The use of these tree species can be expanded by improving their resistance properties. For this purpose, it can be recommended to determine the ideal condensation rate, and to condense with the steaming method in order to determine the minimum springing rate. Sofuoğlu et al. (2023) treated Uludağ fir wood at different densities (0%, 20% and 40%) with thermo-mechanical treatment, and reported that the roughness values increased with the increase in compression ratio (from 0% to 40%).

It is known in the literature that the mechanical strength of wood species with low specific gravity, and low commercial value is increased by compaction. Due to this feature, it can be thought that condensed wood materials can be used in places such as wall coverings, floor coverings, work benches, garden furniture. As a suggestion, it can work to determine the processing properties, mechanical performance, and surface treatment performance of different wood species by subjecting them to the densification process.

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