Original article

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Density, hardness and strength properties of densified fir and aspen woods pretreated with water repellents

<https://doi.org/10.1515/hf-2020-0075>

Received March 21, 2020; accepted July 14, 2020; published online August 24, 2020

Abstract: In this study, the effect of thermo-mechanical densification on the density, hardness, compression strength, bending strength (MOR), and modulus of elasticity (MOE) of fir and aspen wood pretreated with water repellents was analyzed. Wood specimens were impregnated with paraffin, linseed oil and styrene after pre-vacuum treatment. Then, the impregnated wood specimens were densified with compression ratios of 20 and 40%, and at 120, 150 and 180 °C. The results indicated that the density, hardness and strength properties of the all densified specimens (untreated and impregnated) increased depending on the compression ratio and temperature. For all tested properties, higher increases were obtained in the paraffin and styrene pretreated specimens compared to untreated samples. However, the increase rates in linseed oil pretreated specimens were generally lower than untreated specimens. Regarding water repellents the most successful results in all tested properties were determined in styrene pretreated specimens. The density, hardness and strength properties of all specimens increased with the increase in compression ratio. On the other hand, the increase in the compression temperature negatively affects the properties of untreated and linseed oil pretreated specimens, while having a generally positive effect on the properties of paraffin pretreated specimens. However, all tested properties of styrene pretreated specimens have increased significantly due to the increase in compression temperature. The increasing strength properties of wood as a result of densification have increased much more with paraffin and especially styrene pretreatment. These combinations can be considered as an

important potential for applications that require more hardness and strength.

Keywords: densification; hardness; impregnation; mechanical strength; water repellent; wood material.

1 Introduction

High quality wood resources are costly and are not always available in large volumes. Modification processes of wood offers the ability to impart high-quality wood characteristics to lower-value wood. Regarding the difficulties in establishing the balance between the available wood resources and the amount of wood use, it is important to increase the service life of wood, its strength properties, and usable wood species. Wood modification has gained importance due to the difficulties in providing quality wood and the increasing number of faster growing and less durable wood species. Wood modification processes can provide more options for both outdoor and indoor applications. Heat treatment, chemical modification, surface modification, different impregnation and densification processes are applied for wood modification (Bäder et al. 2018; Rowell 2012; Sandberg et al. 2017).

The densification modification makes it possible to give new improved properties to wood species with low strength and quality properties. In this way, the economic importance of low-competitive wood species in the sector increases and can be used in a wider area (Laskowska 2020; Sandberg et al. 2013). The densification processes are based on increasing the wood density by reducing the void volume of the wood material. The main objective of the densification processes is to improve the mechanical properties, hardness, and abrasion resistance of the natural wood, especially for low-density species (Bäder et al. 2018; Laine et al. 2013). With the densification, the surface smoothness and bonding quality properties of the wood can also be increased (Bekhta et al. 2014; Büyüksarı 2013; Candan et al. 2010; Diouf et al. 2011; İmirzi et al. 2014). After densification of the wood, it is possible to obtain a higher

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specific strength than that of most structural metals and alloys (Song et al. 2018).

Many methods have been developed for the densification of wood based on mechanical compression under heat and/or steam conditions, impregnation with different resins, or combined use of mechanical compression and resin processes (Inoue et al. 1993a, b; Kamke and Sizemore 2008; Neyses et al. 2020; Pelit et al. 2014; Sandberg et al. 2013; Seborg et al. 1962; Song et al. 2018; Tabarsa and Chui 1997; Welzbacher et al. 2008). Many of the densification processes make wood in the compressed state very sensitive to moisture. For this reason, the densified wood almost completely returns to its dimensions prior to compression in contact with water or when exposed to high relative humidity. This phenomenon is referred to as set-recovery (Laine et al. 2016; Navi and Heger 2004). In the densification made with resins, the brittleness of the densified wood increases due to the properties of the resins used (Kollmann et al. 1975; Seborg et al. 1962). In addition, resin processes adversely affect the natural structure and sustainability of wood, are costly and cause color change in wood (Morsing 2000; Navi and Heger 2004). Although mechanical densification is used to improve the properties of wood products, it can damage the wood structure during pressing. Excessive compression in wood can cause adverse effects, such as heavier products, higher set-recovery, greater volume loss, and low gluebond properties due to wood cell wall collapse or breakage (Bekhta et al. 2020; Tabarsa and Chui 1997; Wang et al. 2006). These adverse side effects (especially dimensional changes) in densified wood limit the industrial application of densified wood.

Many studies on mechanical densification of wood have focused on the permanent fixation of compressed thickness using different chemical or thermal treatment methods before, during or after densification (Dubey et al. 2016; Dwianto et al. 1997; Fang et al. 2011; Gabrielli and Kamke 2010; Inoue et al. 1993a, b; Kamke and Sizemore 2008; Kariz et al. 2017; Kutnar and Kamke 2012; Laine et al. 2016; Navi and Girardet 2000; Rassam et al. 2012). In our previous study helped support the development of present study, the effect of pre-impregnation processes with water-repellent agents (linseed oil, paraffin, styrene) on the hygroscopicity and dimensional stability of thermo-mechanical densified wood materials was determined (Pelit and Emiroglu 2020). According to the results of the study, the dimensional changes were minimized in styrene pretreated specimens and water repellent effectiveness was close to 100% in these specimens. Findings of physical properties were quite promising for densified wood. The

current study was planned to help determine the usage areas of modified wood with impregnation and densification processes. The objective of present study was to determine the effect of thermo-mechanical densification on the hardness and strength properties of fir and aspen wood impregnated with water repellents.

2 Materials and methods

2.1 Wood material

In this study, fir (*Abies bornmuelleriana* Mattf.) and aspen (*Populus tremula* L.) woods, which have relatively low densities (fir: 450 kg m^{-3} , aspen: 370 kg m^{-3}), were used. Wood materials were selected randomly from a timber company in Düzce, Turkey. Two different boards of the same batch were used for the wood material of each species. Specimens were cut in rough sizes from sapwood of boards, in accordance with the present study methodology. The specimens were subjected to natural drying to approximately 12% moisture content, and then cut to the dimensions of $300 \text{ mm} \times 20 \text{ mm}$ (longitudinal direction $\times$ tangential direction) and three different thicknesses 20 mm (for undensified specimens), 25 and 33.3 mm (radial direction). The test specimens were prepared in a number sufficient to accommodate eight repetitions ($n = 8$) for each variable in the study. To ensure homogeneity between the groups, the wood material of two different boards of wood species was distributed equally to each group. Before impregnation, the specimens were stored in a drying oven until they reached a stable weight at 70°C and weighed.

2.2 Impregnation

As water repellents, paraffin, linseed oil and styrene were used for the impregnating agents. Factors such as high water repellency and low cost were effective in the selection of impregnating agents. A cylindrical tank assembly with a vacuum holder was used in the impregnation of the wood specimens in accordance with ASTM D 1413-76 (1976) standard. With this arrangement, a pre-vacuum equivalent pressure of 760 mm Hg^{-1} was applied to the specimens for 60 min. The impregnation solutions were then diffused into the specimens by holding at atmospheric pressure for 24 h. In order to prevent the melted paraffin from solidifying again, the specimens in the paraffin solution were held at 80°C for 24 h (Pelit and Emiroglu 2020). Afterwards, the paraffin- and linseed-oil treated specimens were kept at a constant temperature of $20 \pm 2^\circ \text{C}$ and relative humidity (RH) of $65 \pm 3\%$. The specimens treated with styrene monomer were wrapped in aluminum foil and then incubated in an oven at 90°C for 2 h to initiate the polymerization process. These specimens were then removed from the oven and subjected to a densification process immediately to complete the polymerization.

2.3 Densification

The impregnated specimens were densified using special metal molds in a hydraulic test press. The pressing parameters applied in the

Table 1: Pressing parameters for densification.

Parameter	Value
Compression temperature (°C)	120, 150 and 180
Compression ratio (%)	20 and 40
Pre-heating time (min)	10
Closing rate (mm min ⁻¹)	60
Compressed holding time (min)	20

thermo-mechanical densification of the specimens are shown in Table 1.

The 25 and 33.3 mm thick specimens were placed inside the channels opened in metal molds as seen in Figure 1. The specimens in the metal molds were placed in the press machine, whose lower and upper plates were heated at target temperatures and pre-heated for 10 min. Then, the specimens were compressed in the radial direction with a loading speed of 60 mm min⁻¹. In order to achieve the targeted thickness (20 mm), the load was maintained until the metal molds came into contact with each other (Figure 2). The compressed specimens were kept under pressure for 20 min and then were removed from the press together with the molds and cooled to room temperature under an average pressure of 5 kg cm⁻² in order to minimize the spring-back effect.

After the densification process, specimens remained in a conditioning cabin (RH 65 ± 3% and 20 ± 2 °C) until they reached a stable weight. The impregnated and densified specimens were then cut into smaller specimens (only in the longitudinal direction) according to the standard of the selected tests ($n = 8$).

2.4 Determination of retention

The retention values of wood specimens impregnated with water repellents were determined using Eq. (1):

$$\text{Retention (kg m}^{-3}\text{)} = (G \times C) / V \times 10 \quad (1)$$

where G is the amount (g) of water repellent absorbed by the specimens, C is the concentration (%) of the water repellent solution, and V is the volume (cm³) of the wood specimens.

2.5 Determination of density and Janka hardness

Air-dry density of the wood specimens was determined according to ISO 13061-2 (2014). The mass of each specimen (M) was measured on an analytical balance, using a sensitivity of ±0.01 g dimensions were measured with a vernier caliper having ±0.01 mm sensitivity, and volume (V) was calculated. The air-dry density (δ) was calculated using Eq. (2):

$$\delta (\text{kg m}^{-3}) = M / V \quad (2)$$

The Janka hardness was accessed in the radial directions according to the procedures described in ISO 13061-12 (2017). Janka hardness values (H_j) were calculated according to Eq. (3):

$$H_j (\text{N mm}^{-2}) = KP \quad (3)$$

where P is the load needed for the loading tip moving at 3 mm min⁻¹ to penetrate to a certain depth (N), and K is the coefficient equal to 4/3 when the loading tip penetrates to a depth of 2.82 mm.

Figure 1: Metal mold and placement of wood specimens. **Figure 2:** Densification of specimens in hot press.

2.6 Determination of compression strength, bending strength and modulus of elasticity

Compression strength parallel to the grain (CS) of the specimens was determined according to ISO 13061-17 (2017). The CS value was calculated by using Eq. (4):

$$CS \text{ (N mm}^{-2}\text{)} = P_{\max}/bd \quad (4)$$

where $P_{\max}$ is the maximum load applied to the specimens (N), b is the width of the specimens (mm), d is the thickness of the specimens (mm).

Bending strength (or modulus of rupture) (MOR) and modulus of elasticity (MOE) of the specimens were determined according to ISO 13061-3 (2014). The MOR and MOE values were calculated using Eqs. (5) and (6):

$$MOR \text{ (N mm}^{-2}\text{)} = 3P_{\max}L/2bd^2 \quad (5)$$

$$MOE \text{ (N mm}^{-2}\text{)} = PL^3/4bd^3\Delta \quad (6)$$

where P is the load difference in elasticity zone (N), L is the supporting span (mm), b is the width of the specimens (mm), d is the thickness (depth) of the specimens (mm), Δ deflection at mid-length below the proportion deflection limit (mm), and $P_{\max}$ is the maximum load when the specimen is broken (N).

2.7 Statistical analyses

Analysis of variance (ANOVA) tests were performed to determine the effect of water repellents on some technological and mechanical properties of densified fir and aspen woods at the 0.05 significance level. Significant differences between the average values of the groups were compared using Duncan's one-way test.

3 Results and discussion

3.1 Retention

The retention values of the fir and aspen wood specimens determined after impregnation with water repellents are shown in Table 2. According to the findings, the highest retention value for both wood species was obtained in specimens impregnated with styrene and the lowest in paraffin-impregnated specimens.

Table 2: Retention values of wood specimens.

Wood species	Retention value (kg m ⁻³)		
	Paraffin	Linseed oil	Styrene
Fir	148 (9)	230 (20)	300 (18)
Aspen	155 (10)	230 (21)	312 (22)

Values in parentheses are standard deviations.

3.2 Density, hardness and compression strength

The thickness of the specimens before and after the densification process and the air-dry density values of the impregnated and densified specimens are shown in Table 3. With respect to water repellents, the maximum density for both wood species was determined in the styrene-impregnated specimens and the minimum was found in the untreated specimens. The density value of all specimens impregnated with water repellents increased. Increases in density can be explained by the absorption of water repellents by the wood material and consequently by the mass increases in the materials.

Density value of the specimens increased after the densification process depending on the compression ratio and temperature. The determined density values were in parallel with the compression ratios and higher density values were obtained at high compression ratio (40%). In terms of compression temperature, the density values of untreated, paraffin and linseed oil-impregnated specimens tend to decrease due to temperature increase (Table 3). It can be said that spring-back increase in untreated specimens as a result of compression temperature increase has an effect on the results (Pelit and Emiroglu 2020). In addition, the amount of evaporation of paraffin and linseed oil absorbed by wood specimens as a result of temperature increase has an effect on the results. On the other hand, in styrene-impregnated specimens, density values increased with increasing compression temperature. This can be explained by the polymerization efficiency in the wood of the styrene monomer at high compression temperature (180 °C). The highest density values for both wood species were determined in the specimens which were compressed by 40% at 180 °C press temperature after impregnation with styrene. The density value of the fir and aspen specimens treated under these conditions increased by 117 and 173%, respectively, compared to the control specimens (Table 3). Density increases in specimens differed depending on wood species, impregnation agent and densification conditions. In previous studies, it was stated that the amount of increase in wood density as a result of compression depended on the properties of wood species, compression ratio and springback effect (Pelit et al. 2018; Rautkari 2012).

ANOVA results show that the effect of water repellents and densification condition factors on hardness and compression strength for fir and aspen woods was statistically significant ($p \leq 0.05$). The highest hardness average regarding water repellents was found to be in the styrene-

Table 3: Thickness before and after compression and density values of impregnated and densified wood specimens.

Water repellents	Densification	Fir				Aspen			
		Initial thickness (mm)	Final thickness (mm)	Density (kg m ⁻³)	Density increase ratio (%)	Initial thickness (mm)	Final thickness (mm)	Density (kg m ⁻³)	Density increase ratio (%)
Untreated	Undensified	20	20	446 (27)	-	20	20	374 (24)	-
	120 °C/20%	25.0	20.5	558 (37)	25	25.0	20.5	486 (40)	30
	120 °C/40%	33.3	20.8	702 (41)	57	33.3	20.6	625 (14)	67
	150 °C/20%	25.0	21.2	520 (22)	17	25.0	21.0	485 (25)	30
	150 °C/40%	33.3	21.5	647 (39)	45	33.3	21.1	595 (28)	59
	180 °C/20%	25.0	20.9	521 (31)	17	25.0	20.8	466 (34)	25
Paraffin	180 °C/40%	33.3	21.7	661 (39)	48	33.3	21.2	601 (39)	61
	Undensified	20	20	558 (35)	25	20	20	483 (33)	29
	120 °C/20%	25.0	20.5	584 (45)	31	25.0	20.5	565 (50)	51
	120 °C/40%	33.3	20.8	728 (61)	63	33.3	20.7	702 (23)	88
	150 °C/20%	25.0	20.6	565 (29)	27	25.0	20.7	552 (30)	48
	150 °C/40%	33.3	20.8	720 (32)	61	33.3	20.9	647 (36)	73
Linseed oil	180 °C/20%	25.0	20.5	569 (27)	28	25.0	20.8	559 (46)	50
	180 °C/40%	33.3	20.4	705 (26)	58	33.3	20.7	683 (30)	83
	Undensified	20	20	509 (39)	14	20	20	480 (48)	28
	120 °C/20%	25.0	20.5	611 (42)	37	25.0	20.7	557 (60)	49
	120 °C/40%	33.3	21.1	767 (31)	72	33.3	21.2	743 (43)	99
	150 °C/20%	25.0	20.6	583 (50)	31	25.0	20.8	581 (56)	55
Styrene	150 °C/40%	33.3	21.2	764 (58)	71	33.3	21.6	650 (41)	74
	180 °C/20%	25.0	20.7	549 (28)	23	25.0	20.9	534 (31)	43
	180 °C/40%	33.3	21.3	684 (15)	53	33.3	21.3	665 (19)	78
	Undensified	20	20	568 (44)	27	20	20	542 (34)	45
	120 °C/20%	25.0	21.1	648 (48)	45	25.0	21.4	588 (32)	57
	120 °C/40%	33.3	21.5	933 (65)	109	33.3	21.8	923 (61)	147
	150 °C/20%	25.0	21.0	651 (27)	46	25.0	20.3	739 (44)	98
	150 °C/40%	33.3	21.0	951 (70)	113	33.3	20.7	1008 (65)	169
	180 °C/20%	25.0	20.4	650 (32)	46	25.0	20.2	720 (51)	92
	180 °C/40%	33.3	20.3	966 (36)	117	33.3	20.2	1023 (51)	173

All values are the results of measurements after conditioning at RH 65 ± 3% and 20 ± 2 °C. Values in parentheses are standard deviations.

impregnated specimens (51 N mm⁻² for fir and 58 N mm⁻² for aspen), while the lowest was obtained in the linseed oil-impregnated and untreated specimens (23 and 24 N mm⁻² for fir and 20 and 21 N mm⁻² for aspen) (Table 4). For undensified specimens, no significant difference was observed between the hardness values of untreated specimens and the hardness values of paraffin and linseed oil-impregnated specimens. In densified specimens, hardness values of linseed oil-impregnated specimens generally tend to decrease. The hardness values of the paraffin and especially styrene-impregnated specimens increased after densification (Figure 3a).

With respect to densification conditions, the highest hardness average was determined in the specimens compressed at 180 °C with the 40% ratio (42 N mm⁻² for fir and 44 N mm⁻² for aspen) and the lowest was found in the undensified specimens (17 N mm⁻² for fir and 15 N mm⁻² for aspen) (Table 4). Hardness values of all the densified specimens increased depending on the compression ratio

and temperature. Hardness values increased as a result of the increase in compression ratio. In terms of compression temperature, the hardness values of untreated, paraffin and linseed oil-impregnated specimens were generally slightly reduced due to the increase in compression temperature. However, the hardness values of styrene-pretreated specimens (compressed at both 20 and 40% ratio) increased significantly due to the increase in compression temperature (Figure 3a). It can be said that the high increase rates of density values of these specimens had an effect on the results. In addition, in styrene-pretreated specimens, significant decreases in equilibrium moisture content (EMC) values due to increase in compression temperature are thought to affect the results (Pelit and Emiroglu 2020). The highest hardness values for both wood species were determined in the specimens compressed with the 40% ratio at 180 °C after treatment with styrene. Compared to control (untreated and undensified) specimens, the hardness values of fir and aspen

Table 4: Duncan’s one-way test results for mean values of hardness, compression strength, MOR and MOE.

Factor	Fir				Aspen			
	Hardness (N mm ⁻²)	Compression strength (N mm ⁻²)	MOR (N mm ⁻²)	MOE (N mm ⁻²)	Hardness (N mm ⁻²)	Compression strength (N mm ⁻²)	MOR (N mm ⁻²)	MOE (N mm ⁻²)
Water repellents								
Untreated	24 c**	57 d	102 c	10930 c	21 c	50 d	87 c	8764 c
Paraffin	26 b	66 b	108 b	11320 b	22 b	58 b	93 b	9119 b
Linseed oil	23 c	59 c	95 d	10510 d	20 c	53 c	82 d	8277 d
Styrene	51 a	81 a	120 a	12270 a	58 a	79 a	113 a	11150 a
Densification								
Undensified	17 d	45 f	73 e	7970 e	15 g	40 f	60 e	5865 e
120 °C/ 20%	25 c	59 e	99 cd	10630 cd	21 f	53 e	85 d	8464 d
120 °C/ 40%	38 b	75 c	120 b	12750 b	36 c	68 c	106 b	10720 b
150 °C/ 20%	25 c	60 e	98 d	10340 d	26 e	55 de	91 c	8884 c
150 °C/ 40%	41 a	78 b	122 b	12860 b	42 b	72 b	109 b	10990 b
180 °C/ 20%	26 c	63 d	102 c	10810 c	28 d	57 d	92 c	9038 c
180 °C/ 40%	42 a	83 a	128 a	13440 a	44 a	77 a	113 a	11340 a

**Statistical group (different letters denote a significant difference).

Figure 3: Hardness and compression strength values of impregnated and densified wood samples.

wood treated under these conditions increased by 448 and 636%, respectively. Furthermore, increases in hardness relative to wood species were proportional to increases in density. Many studies have reported that the hardness of the densified wood increases due to the increase in compression ratio or density (Boonstra and Blomberg 2007; Pelit and Yorulmaz 2019; Rautkari et al. 2009; Ünsal et al. 2011). Furthermore, it is well known that the hardness decreases as the moisture content increases up to the fiber saturation point in the wood material and the wood in full dry state has the highest hardness.

Regarding water repellents, the highest compression strength average in the styrene-impregnated specimens was 81 N mm^{-2} for fir and 79 N mm^{-2} for aspen, while the lowest was obtained in the untreated specimens with 57 N mm^{-2} for fir and 50 N mm^{-2} for aspen (Table 4). In the fir and aspen specimens (especially styrene-impregnated) treated with water repellents, the compression strength was generally increased. However, the compression strength values of untreated and linseed oil-impregnated specimens were similar (Figure 3b). Increased compression strength can be attributed to increases in density after impregnation. In addition, decreases in spring-back values of the impregnated specimens affected the results (Pelit and Emiroglu 2020).

The highest compression strength average regarding densification conditions was found to be in the specimens compressed with the ratio of 40% at 180°C (83 N mm^{-2} for fir and 77 N mm^{-2} for aspen) and the lowest was found in the undensified specimens (45 N mm^{-2} for fir and 40 N mm^{-2} for aspen) (Table 4). Compression strength increased in all wood specimens (untreated and impregnated) depending on the compression rate and temperature after the densification process. Higher compression strength was obtained in the specimens densified with high compression ratio (40%). The compression strength of untreated fir and aspen specimens tended to decrease with increasing compression temperature. The compression strength of the impregnated specimens increased due to the increase in the compression temperature. For fir wood, compression strength in the untreated, linseed oil, paraffin and styrene-treated specimens compressed at 40% ratio increased 73, 107, 80 and 191%, respectively. For aspen wood under the same conditions, compression strength increased 81, 118, 82 and 235%, respectively (Figure 3b). After densification, especially in the styrene pretreated specimens, considerable increases in strength were achieved. Strength increases of specimens can be explained by increases in density. In previous studies, it was reported similarly that the strength properties of densified wood are higher than that of untreated wood and compression

strength generally increases in proportion with the increase in density (Blomberg et al. 2005; Morsing 2000; Pelit et al. 2018).

3.3 Bending strength and modulus of elasticity

According to ANOVA results, the effect of water repellents and densification conditions factors on bending strength (MOR) and modulus of elasticity (MOE) for fir and aspen woods was statistically significant ($p \leq 0.05$). The maximum MOR and MOE for both wood species in the water repellents level was obtained in the styrene-impregnated specimens and the minimum was found in the linseed oil-impregnated specimens (Table 4). The MOR and MOE values of all specimens (undensified and densified) impregnated with paraffin and styrene increased compared to untreated specimens. For undensified specimens, both MOR and MOE values in untreated and linseed oil-impregnated wood specimens were determined close to each other. For densified specimens (especially compressed by 40%), the MOR and MOE values were measured lower in specimens impregnated with linseed oil compared to other impregnation materials (including untreated specimens). The most successful results in terms of MOR and MOE for all conditions were observed in styrene-impregnated specimens (Figure 4a and b).

The maximum MOR and MOE regarding densification conditions was determined in the specimens compressed at the ratio of 40% at 180°C , while the minimum was obtained in the undensified specimens (Table 4). As with other tested properties in this study, the MOR and MOE values of all densified specimens (untreated and impregnated) increased depending on the compression temperature and compression ratio. In densified fir and aspen specimens, MOR and MOE increased with the increase in compression ratio (Figure 4). The results are consistent with the results of previous studies (Kutnar et al. 2008; Pelit and Yorulmaz 2019; Tabarasa and Chui 1997; Kutnar et al. 2008; Pelit and Yorulmaz 2019). On the other hand, as a result of the increase in the compression temperature, MOR and MOE were affected differently depending on the water repellent type. The effect of the compression temperature on the MOR and MOE strength of untreated specimens is not evident. While the effect of compression temperature on MOE values of paraffin-impregnated specimens is not pronounced, MOR values are generally increased with increasing temperature. In linseed oil-impregnated specimens, the MOR values decreased due to the increase in temperature and the MOE values tended to decrease. In both wood species impregnated with styrene, both MOR

Figure 4: Average MOR and MOE values of impregnated and densified wood samples.

and MOE strength increased due to the increase in compression temperature. When evaluated in general, the highest MOR and MOE values after impregnation and densification processes were determined in the styrene pretreated specimens compressed at the ratio of 40% at 180 °C. Compared to control specimens, the MOR increased 119 and 154%, respectively, and the MOE increased 107 and 172%, respectively, in the fir and aspen specimens treated under these conditions. These significant increases in MOR and MOE can be explained by decreases in EMC and spring-back values of the styrene pretreated and densified specimens (Pelit and Emiroglu 2020) and increases in specimen density. In the literature, it was stated that the treatment of wood with vinyl monomers such as styrene is a promising way to increase water repellency, dimensional stability, and mechanical strength (Che et al. 2019; Rowell 2012; Sandberg et al. 2017). The literature knowledge is supported the findings of this study.

4 Conclusion

In the present study, density, hardness and strength properties of impregnated and densified fir and aspen wood were analyzed. After densification, all tested properties of

non-impregnated (untreated) and impregnated specimens increased depending on pressing conditions. These increases were higher in paraffin- and styrene pretreated specimens than untreated specimens. However, the increase rates (except density and compression strength) in linseed oil pretreated specimens were lower than untreated specimens. The most successful results in terms of water repellents were obtained in styrene pretreated specimens. Significant increases were determined in all tested properties of these specimens. In pressing processes, all tested properties of wood specimens increased as a result of the increase in compression ratio. On the other hand, due to the increase in compression temperature, the hardness, MOR and MOE tend to decrease in linseed oil pretreated specimens. In general, an increase trend was observed in strength properties of paraffin pretreated specimens. However, the increase in compression temperature significantly affected all selected properties of styrene pretreated fir and aspen specimens. Superior increases were achieved in the density, hardness and strength properties of these specimens with the increase in compression temperature and ratio.

The findings of this study showed that due to thermo-mechanical densification, the increased hardness and strength properties of wood specimens increased much more with paraffin and especially styrene pretreatment.

Therefore, pretreatment with styrene can be recommended especially prior to densification to impart high-quality wood characteristics to wood species with low hardness and strength value. Wood modified in this way can also be a powerful alternative for areas requiring high strength and hardness, such as carrier applications and flooring.

Author contribution: All the authors have accepted responsibility for the entire content of this submitted manuscript and approved submission

Research funding: The authors are grateful for the support of the Research Fund of Duzce University, grant no. BAP-2017.07.01.522.

Conflict of interest statement: The authors declare no conflicts of interest regarding this article.

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