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PROPERTIES OF THREE-LAYER ASPEN (*POPULUS TREMULA* L.) PARTICLEBOARDS WITH LAYERED INCLUSION OF TURKEY OAK (*QUERCUS CERRIS* L.) PARTICLES

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ABSTRACT

The production of particleboard is influenced by various technological and technical factors that affect both quality and economic performance. Among these, board density is particularly important-higher density enhances mechanical properties but increases production costs. Therefore, medium-density particleboards are typically manufactured from softwood species, whose low density provides favorable strength characteristics. In contrast, hardwood species often reduce mechanical performance, limiting their proportion in the mixture to 20–30%. However, in the Republic of Bulgaria, 32% of forested areas are covered with oak species, including 9% with turkey oak (*Quercus cerri*s L.), making its exclusion from production impractical. This study explores the potential for greater use of turkey oak in three-layer particleboards made from aspen. Layers of turkey oak particles were added to the face layers at 10%, 20% and 30%. In two additional panels, turkey oak was included in the core layer at 10% and 20%, resulting in a total content of 40% and 50%. The panels were manufactured under laboratory conditions at 180°C, 2.3 MPa and 330 seconds, with a target density of 640 kg·m^{-3}. The results showed consistently high values of modulus of rupture and modulus of elasticity at all levels of turkey oak inclusion.

Key words: three-layer particleboards; separate layers; turkey oak particles; aspen; physical and mechanical properties

INTRODUCTION

The wood content in particleboards (PB) was about 90%, which is why their properties heavily depended on the type of wood raw material used in their composition. The type of wood raw material also affected the production process parameters as well as the cost of the finished boards. The density of the wood species used to produce the wood particles was an important technological factor that influenced the physical and mechanical properties of PB. The compaction of the used wood and the resulting higher-density PB was defined as the compaction ratio, as described by researchers such as Kollmann *et al.* (Kollmann *et al.* 1974), Moslemi (Moslemi 1974), and Kelly (Kelly 1977).

According to Moslemi and Maloney (Moslemi 1974, Maloney 1993), the wood compaction ratio should not be less than 1.3 to ensure a larger contact area between particles and more adhesive bonds. Moslemi stated that the higher the compaction ratio, the higher the mechanical strength of the PB would be.

An increase in the compaction ratio was achieved by using low-density wood species. Studies by Grigoriu (Grigoriu 1981), Clad (Clad 1981), Xu *et al.* (Xu *et al.* 2004), and Haelvoet and Medved (Haelvoet and Medved 2009) established that the use of low-density wood increased the compaction ratio, which strongly and positively affected the properties of particleboards (PB). Wong *et al.* (Wong *et al.* 1999) reported that using low-density wood in the core layer increased the compaction of the particles, resulting in greater contact between them and an increase in the internal bond strength of PB.

A study conducted by Warmbier *et al.* (Warmbier *et al.* 2014) found that increasing the proportion of Willow particles in the core layer (made from a mix of willow and pine) led to improvements in internal bond strength, screw withdrawal resistance, and reductions in water absorption and thickness swelling. Another study by Yosifov *et al.* (Yosifov *et al.* 1991) evaluated the suitability of different wood species as raw materials for the production of PB with a density of 700 kg·m^{-3}. They reported the following wood compaction ratios: spruce – 2.00; poplar – 1.93; aspen – 1.83; scots pine – 1.83; willow – 1.67; birch – 1.18; linden – 1.12; beech – 1.01; and oak – 0.86. Hardwood deciduous species such as beech and oak had a low compaction ratio in medium-density PB, and their inclusion resulted in a decrease in mechanical properties.

Research by Setunge *et al.* (Setunge *et al.* 2009) showed that particleboards made from hardwood had lower mechanical properties compared to boards made from softwood. Many studies aimed to increase the percentage of hardwood used in the composition of particleboards. The study by Iždinský *et al.* (Iždinský *et al.* 2024) demonstrated that the addition of 30 weight parts of Beech wood particles led to a decrease in the modulus of rupture and modulus of elasticity of particleboards. On the other hand, it improved the internal bond strength at the surface of the face layer and reduced water absorption and thickness swelling of the boards.

According to the study by Neils and Mai (Neils and Mai 2019), who produced particleboards from a mix of hardwood and softwood with compaction ratios of 1.2 and 1.6, a higher compaction ratio of 1.6 improved the modulus of rupture and modulus of elasticity of the boards, while a lower compaction ratio of 1.2 improved the internal bond strength. De Bazzetto *et al.* (De Bazzetto *et al.* 2019) and Dias *et al.* (Dias *et al.* 2005) reported that low-density wood materials were better suited for the production of medium-density particleboards, as they allowed a compaction ratio up to 1.3, which increased the contact area between particles during hot pressing and led to improved adhesive bonding between particles.

According to Rofii *et al.* (Rofii *et al.* 2014), high-density wood species were often unsuitable for the production of particleboard due to their low compaction ratio when used in medium-density particleboards. The study by Tayo *et al.* (Tayo *et al.* 2020) on particleboards made from black locust (*Robinia pseudoacacia* L.) wood with a density of 650 kg·m^{-3} and various types of adhesives found that boards meeting the requirements of the EN 312 standard could be produced.

The present study aimed to determine how the physico-mechanical properties of three-layer medium-density particleboards (with a density of 640 kg·m^{-3}) changed when wood particles from the softwood of aspen (*Populus tremula* L.) were used to form the core layer, where the board density was lower, and wood particles from the hardwood of turkey oak (*Quercus cerris* L.) were used to form the face layers of the boards, where the density was higher. The inclusion of turkey oak particles in the face layers aimed to achieve a compaction ratio of the turkey oak hardwood above 1.0. This sought to plasticize the wood particles during the hot pressing process, increase the contact areas between them, and thereby improve the bonding between particles. Achieving a compaction ratio of turkey oak wood above 1.0 helped the particles transfer their inherent mechanical strength to the particleboard to a greater extent.

The second objective of the study was to determine whether the inclusion of layers of turkey oak particles in the composition of a three-layer particleboard-extending from the surface of the face layers toward the interior of the board (toward the core layer), with the core layer composed of particles from aspen (*Populus tremula* L.) – could increase the proportion of hardwood to up to 50% of the composition of medium – density particleboards, and whether this led to a deterioration in their physico-mechanical properties.

MATERIALS AND METHODS

2.1. MATERIALS

The wood particles used in the experiment were produced from turkey oak (*Quercus cerris* L.) with a wood density of 810 kg·m^{-3} (at a moisture content of 11.8%) and aspen (*Populus tremula* L.) with a wood density of 380 kg·m^{-3} (at a moisture content of 12.2%). These particles were obtained through a two-stage chipping process of roundwood. Roundwood with a diameter of 18–22 cm and a length of 1.0 meter was chipped into industrial wood chips using a mobile drum chipper Vermeer BC 1000 XL (Vermeer Corporation, Iowa, USA). The resulting wood chips were then ground into particles using a hammer mill model FCH-500 (SKSM "SILA", Yambol, Bulgaria), fitted with screens with mesh sizes of 10 and 20 mm. The particles were subsequently dried to a moisture content of 9.6% for turkey oak and 8.7% for aspen.

Particle size classification was carried out using a screening machine with sieve openings ranging from 6.3 mm to 0.1 mm. The particles were separated by size into face layer and core layer fractions, as shown in Figure 1. Particles larger than 6.3 mm and smaller than 0.1 mm were removed.

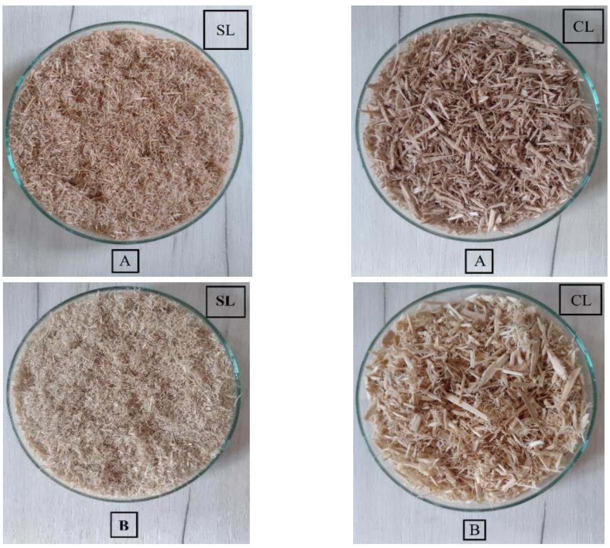

Figure 1: Wood particles: SL – face layer; CL – core layer; A – turkey oak particles; B – aspen particles.

The fractional composition of turkey oak and aspen particles was presented in Figure 2.

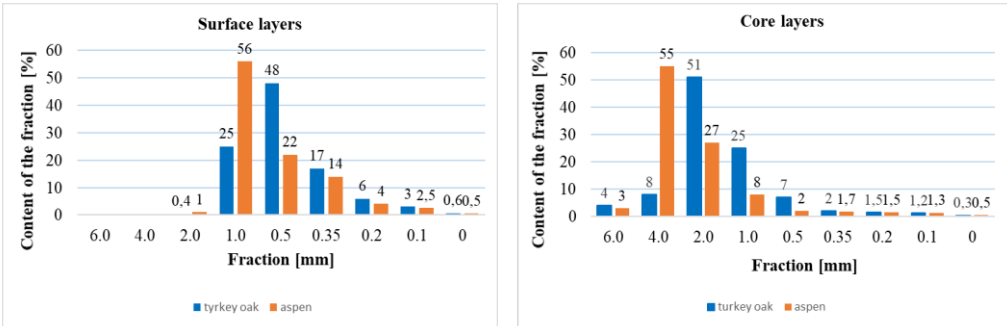

Figure 2: Fractional composition of the turkey oak and aspen particles – for face layers (SL) and core layer (CL).

2.2. ADHESIVES

The industrially produced urea-formaldehyde resin powder, commercially known as Sadekol-P410, was manufactured by Henkel GmbH, Germany. Ammonium sulfate ($(NH_4)_2SO_4$) was used as a hardener for the resin in the core layer, in an amount of 1.5%. The hardener was added to the liquid adhesive as a 20% aqueous solution before being applied to the particles. The properties of the urea-formaldehyde adhesive were presented in Table 1.

Table 1: Properties of urea-formaldehyde (UF) adhesive.

Characteristic	Unit	Value
Concentration	%	54±1
Density	kg.m^{-3}	1220 to 1240
Dynamic viscosity	Pa.s	0.5
pH	-	7.5 to 7.8
Curing time (100°C)	s	50

2.3. PRODUCTION OF PANELS

The three-layer particleboard was produced with a target density of 640 kg·m^{-3}. The SL/CL ratio of the boards was 30/70. The wood particles for the face layer (SL) were placed in a laboratory mixer, where, during the mixing process, urea-formaldehyde adhesive was sprayed onto the particles in an amount of 12%, while the adhesive was applied to the particles for the core layer (CL) in an amount of 8%. A mat was then formed on steel sheets within a frame measuring 500 × 500 mm. Particles from each wood species were poured in separate layers during the formation of the wood mat. Half of the face layer particles from turkey oak were evenly spread over the steel sheet, followed by the other half of the face layer particles from aspen. The core layer particles were then spread over them, followed by the face layer particles from aspen, and finally, the second half of the face layer particles from turkey oak were spread on top.

The particle mat was placed in the press using the metal sheets, with two metal strips of 18 mm thickness placed to achieve the exact thickness of the boards. The hot pressing process of the particles was carried out on a hydraulic laboratory press with electric heaters – PMC ST 100 (Manni – S.P.A, Italy). The hot pressing temperature was 180°C, with a specific pressing pressure ranging from 2.3 to 0.6 MPa and a pressing time of 330 s. The hot pressing mode was presented in Table 2.

Table 2: Hot pressing mode of three-layer particleboards.

Stage	Specific pressure, MPa	Temperature of hot plates, °C	Time, s
Closing	0 – 2.3	180	10
1	2.3	180	30
2	1.2	180	180
3	0.6	180	120
Opening	0.6 – 0	180	20

The parameters at which the three-layer particleboards were made were presented in Table 3.

Table 3: Individual types of manufactured particleboards.

Variant	Percentage of layered inclusion of particles in the face layers of the particleboards, %		Percentage of layered inclusion of particles in the core layer of the particleboards, %	
	Percentage of layered inclusion of turkey oak particles, %	Percentage of layered inclusion of aspen particles, %	Percentage of layered inclusion of turkey oak particles, %	Percentage of layered inclusion of aspen particles, %
A100	0	30	0	70
TO10A90	10	20	0	70
TO20A80	20	10	0	70
TO30A70	30	0	0	70
TO40A60	30	0	10	60
TO50A50	30	0	20	50
REF*	9	21	21	49

A – aspen; TO – turkey oak.

*The reference board was produced by forming both the face and core layers from a mixture of turkey oak and aspen particles in a 30/70 ratio.

The cross-sectional structure of the produced particleboards is given in Figure 3.

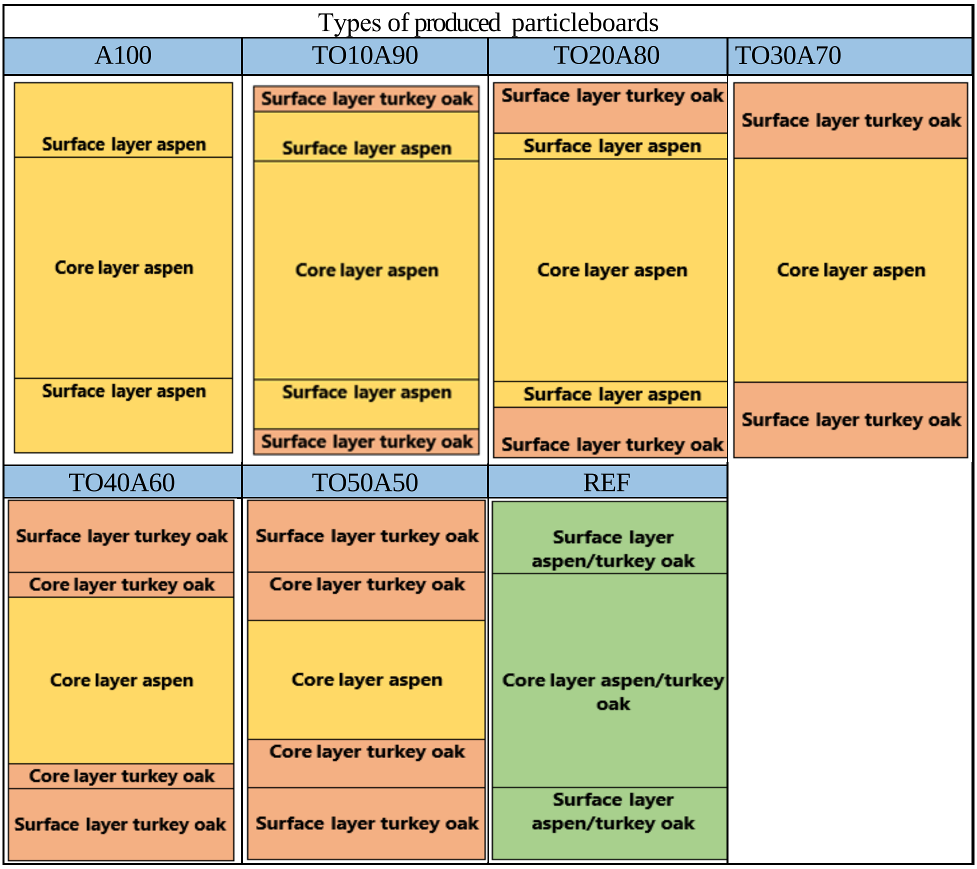

Figure 3: Cross-section of produced particleboards.

The produced panels were cooled and left to rest for 24 hours in a room with a relative air humidity of 65 ± 5% and an air temperature of 20 ± 2°C for conditioning. The particleboards were then cut into test specimens in accordance with the requirements of EN 326-1 (EN 326-1, 1993) and EN 326-2 (EN 326-2, 2010).

The physical properties of the boards were determined as follows: density EN 323 (EN 323, 1993), moisture content EN 322 (EN 322, 1993), water absorption (WA) and thickness swelling (TS) after 2 and 24 hours EN 317 (EN 317, 1993), modulus of rupture (MOR) and modulus of elasticity (MOE) EN 310 (EN 317, 1993), internal bond (IB) EN 319 (EN 319, 1993) and surface soundness (SS) EN 311 (EN 311, 2003). Each physical and mechanical property was determined from a sample of 8 test specimens.

The mechanical properties were determined using a universal testing machine HST-50E (Jinan Hensgrand Instrument Co. Ltd, China). The density profile of each board was tested using the DPX-300 X-ray densitometer (IMAL, Modena, Italy). The density was measured at intervals of 0.05 mm. The following parameters of the density profile of the particleboards were determined: the maximum density of the face layers (DMaxSL) and the central density of the core layer (DCentCL). Two values of the maximum density of the face layer (DMaxSL) were determined on the left and right sides of the particleboard.

The compaction ratio of the wood in the face layers (CRsl) was determined by the following equation: CRsl = DMaxSL/Dturkey oak, where Dturkey oak was the density of the wood of turkey oak. The compaction ratio of the wood in the core layer (CRcl) was determined by the following equation: CRcl = DCentCL/Daspen, where Daspen was the density of the wood of aspen.

The classification of the boards was carried out according to the European standard EN 312, taking into account the requirements for board types P2, P3, and P4, with a thickness between 13 mm and 20 mm.

3. RESULTS AND DISCUSSION

3.1. RESULTS OF STATISTICAL ANALYSIS

The statistical analysis of the results was carried out using the using the software product Excel/Data Analysis (Microsoft Corporation, Redmond, Washington, USA). The analysis was based on the t-test or ANOVA (Fisher's F-test), with a significance level (p) of 0.05. The physical-mechanical properties of the particleboards were strongly influenced by their density. The average density of the produced particleboards ranged from 635 $kg \cdot m^{-3}$ to 657 $kg \cdot m^{-3}$. After performing a t-test ($\alpha = 0.05$) to determine statistical differences between two samples for the density of test specimens, the following p-values were obtained: particleboard of type A100/TO10A90 – $p = 0.464$; TO10A90/TO20A80 – $p = 0.588$; TO20A80/TO30A70 – $p = 0.156$; TO30A70/TO40A60 – $p = 0.374$; TO40A60/TO50A50 – $p = 0.142$; TO50A50/REF – $p = 0.626$. All p-values were > $\alpha = 0.05$, which meant there was no statistically significant difference in the compared indicators, and therefore, changes in the density of the particleboards did not affect their properties.

The analysis of variance (ANOVA) the properties of the particleboards was presented in Table 4.

Table 4: Analysis of variance (ANOVA) the properties of particleboards

Water absorption after 2 h						
Source of Variation	SS	DF	MS	F	P-value	F critical
Between Groups	274.32	4	68.58	13.16	1.21E-06	2.64
Water absorption after 24 h						
Source of Variation	SS	DF	MS	F	P-value	F critical
Between Groups	245.88	4	61.47	15.68	1.92E-07	2.64
Thickness swelling after 2 h						
Source of Variation	SS	DF	MS	F	P-value	F critical
Between Groups	73.80	4	18.45	11.56	4.35E-06	2.64
Thickness swelling after 24 h						
Source of Variation	SS	DF	MS	F	P-value	F critical
Between Groups	114.14	4	28.53	8.37	7.57E-05	2.64

Modulus of rupture						
Source of Variation	SS	DF	MS	F	P-value	F critical
Between Groups	4.68	4	1.17	0.57	0.68	2.64
Modulus of elasticity						
Source of Variation	SS	DF	MS	F	P-value	F critical
Between Groups	301531.65	4	75382.91	1.83	0.14	2.64
Internal bond						
Source of Variation	SS	DF	MS	F	P-value	F critical
Between Groups	0.02	4	0.0066	1.80	0.15	2.64
Surface Soundness						
Source of Variation	SS	DF	MS	F	P-value	F critical
Between Groups	0.58	4	0.14	15.35	2.41E-07	2.64

(Where: SS – sum of squares, DF – degrees of freedom, MS – variance, F – Fisher's F-test, P – significance level, F critical – Fisher's critical value).

From the data presented in Table 4, it is found that the values of the Fisher-F criterion are lower than the critical values of the Fisher criterion (F < Fcritical) for Modulus of rupture, Modulus of elasticity and Internal bond, which indicates that the increase in the layered inclusion of turkey oak particles does not affect these properties of aspen particle boards.

3.2. RESULTS FOR THE PHYSICAL AND MECHANICAL PROPERTIES OF PARTICLEBOARD

The established physical and mechanical properties of the produced particleboards were presented in Table 5.

Table 5: Physical and mechanical properties of produced particleboards

Properties of particleboards	Dimension	Types of particleboards						
		A100	**TO10A90**	**TO20A80**	**TO30A70**	**TO40A60**	**TO50A50**	**REF**
Density	($kg \cdot m^{-3}$)	657 (26.83)	644 (29.36)	635 (19.71)	650 (24.49)	638 (19.7)	655 (28.9)	646 (30.58)
Thickness swelling (TS) after 2 h	(%)	22.7 (1.5)	22.3 (1.0)	21.6 (1.4)	18.3 (0.6)	20.6 (0.9)	20.9 (1.8)	18.8 (1.3)
Thickness swelling (TS) after 24 h	(%)	29.2 (2.2)	28.2 (1.1)	27.9 (2.5)	23.5 (1.4)	25.9 (0.9)	25.9 (2.4)	22.5 (1.0)

Properties of particleboards	Dimension	Types of particleboards						
		A100	TO10A90	TO20A80	TO30A70	TO40A60	TO50A50	REF
Water absorption (WA) after 2 h	(%)	83.4 (2.9)	82.3 (2.0)	80.5 (2.7)	74.4 (1.8)	79.1 (2.5)	79.4 (2.0)	76.5 (1.7)
Water absorption (WA) after 24 h	(%)	96.7 (2.4)	90.5 (1.6)	88.9 (2.2)	83.1 (2.9)	87.6 (2.2)	87.7 (1.6)	83.8 (1.7)
Modulus of rupture (MOR)	(N.mm^{-2})	14.0 (1.6)	14.3 (1.82)	14.7 (0.9)	14.1 (1.65)	13.7 (1.0)	14.5 (1.4)	13.9 (2.0)
Modulus of elasticity (MOE)	(N.mm^{-2})	2623 (150.3)	2379 (230.5)	2336 (153.7)	2237 (209.5)	2129 (214.7)	2296 (197.1)	2374 (217.3)
Internal bond (IB)	(N.mm^{-2})	0.45 (0.03)	0.48 (0.04)	0.49 (0.06)	0.55 (0.07)	0.51 (0.06)	0.54 (0.05)	0.47 (0.05)
Surface Soundness (SS)	(N.mm^{-2})	0.83 (0.07)	0.89 (0.09)	1.1 (0.1)	1.2 (0.12)	1.0 (0.08)	1.09 (0.07)	1.15 (0.1)

Note: Average values were determined from 8 samples. Standard deviations are in the parentheses. The moisture content in the produced particleboards ranged from 6.5% to 7.2%.

The quantitative parameters estimated in the density profile of three-layer aspen particleboards at different percentages of layered inclusion of turkey oak particles in the composition of the boards are presented in Table 6.

Table 6: Quantitative parameters evaluated in the density profile of three-layer aspen particleboards with different percentage of layered inclusion of turkey oak particles

Properties	Dimension	Types of particleboards						
		A100	TO10A90	TO20A80	TO30A70	TO40A60	TO50A50	REF
Density mean	($kg\cdot m^{-3}$)	657	644	635	650	638	655	646
Density central	($kg\cdot m^{-3}$)	555	524	551	525	545	552	545
Density max left	($kg\cdot m^{-3}$)	904	892	897	926	860	865	898
Density max right	($kg\cdot m^{-3}$)	915	912	881	910	858	848	907
Density central/mean	(%)	0.86	0.82	0.84	0.81	0.84	0.86	0.83

3.3. WATER ABSORPTION AND THICKNESS SWELLING

The conducted analysis of variance (ANOVA) on the water absorption of the particleboards (Table 4) showed a statistically significant difference in the values of this property among the different boards. The layered inclusion of turkey oak particles in the face and core layers of the boards affected the water absorption of the three-layer aspen particleboards. Increasing the proportion of turkey oak particles from 10% to 50% led to a reduction in the water absorption of the particleboards after both 2 and 24 hours.

The measured values of water absorption were high, with the highest water absorption observed in boards made with aspen particles. At a 10% layered inclusion of turkey oak particles, the 24-hour water absorption was 90%, which represented a reduction of 6.2%. Increasing the proportion of turkey oak particles from 10% to 50% resulted in a slight further reduction in water absorption by 3.3% (down to 87%). This indicated that the turkey oak particles in the surface and core layers of the boards became significantly compacted against each other, reducing the voids between them. The face layers was subjected to pressure from one side by the hot plates of the press, and from the other side by the core layer, which consisted of larger and thicker aspen particles. The strong influence of the core layer made of aspen wood particles and its fractional composition led to high pressing resistance, which in turn resulted in densification of the face layer of the particleboard, according to Schneider *et al.* (Schneider *et al.* 2018) and Benthien *et al.* (Benthien *et al.* 2018).

The results for thickness swelling of the particleboards made from aspen after 2 and 24 hours showed statistically significant differences in the values of this property between the different boards. Increasing the layered inclusion of turkey oak particles from 0% to 50% led to a reduction in thickness swelling of the three-layer aspen boards. Similar results were reported by Iždinský *et al.* (Iždinský *et al.* 2024) when the proportion of beech particles in the composition of particleboards increased. The measured thickness swelling values were high, with the highest value of 29.2% observed for boards made from 100% aspen particles (after 24 hours). At 10% layered inclusion of turkey oak particles, the thickness swelling was 28.2%, and at 50% inclusion, it dropped to 25.9%. These thickness swelling values were similar to the results presented by Żabowski *et al.* (Żabowski *et al.* 2024) for three-layer particleboards with a core layer made of 100% willow particles, where the lowest thickness swelling value achieved was 24.5%. The study by Eslah *et al.* (Eslah *et al.* 2012) found a thickness swelling of 17.3% for single-layer particleboards made from poplar with a density of 623 $kg \cdot m^{-3}$ and 8% UF adhesive. The results presented in Nourbakhsh's (Nourbakhsh 2009) study for single-layer particleboards made from three-year-old branches of different poplar species with a density of 700 $kg \cdot m^{-3}$ showed thickness swelling (after 24 hours) ranging from 21.7% to 27.6%.

Increased layered inclusion of turkey oak particles in the composition of three-layer aspen particleboards resulted in a decrease in water absorption and thickness swelling, both after 2 hours and after 24 hours. At 100% aspen particle content, water absorption reached 96.7% (after 24 hours), while at 50% turkey oak particle content in one layer, it decreased to 87.7% (after 24 hours). Thickness swelling at 100% aspen content was 29.2% (after 24 hours), while at 50% turkey oak particle content in one layer, it dropped to 25.9% (after 24 hours).

The reduction in thickness swelling was likely due to the decreased percentage of aspen particles. Because of the lower density of aspen wood (380 $kg \cdot m^{-3}$), a larger volume of aspen particles was required to reach the desired particleboard density of 640 $kg \cdot m^{-3}$. This resulted in more wood fibers being embedded per unit volume. When particleboards made of 100% aspen were immersed in water, they swelled more due to the higher amount of wood fibers. Increasing the particle layers of turkey oak reduced the proportion of aspen particles, leading to a reduction in thickness swelling of the particleboards.

3.4. MODULUS OF RUPTURE AND MODULUS OF ELASTICITY

The performed analysis of variance (Table 4) shows that there is no statistically significant difference in the compared values for modulus of rupture (MOR) and modulus of elasticity (MOE) among the tested boards. The increase in layered inclusion of particles of turkey oak does not influence the MOR and MOE of the three-layer particleboards made from aspen. In all percentage of layered inclusion turkey oak particle at 10% to 50%, the particleboards exhibit MOR values above 14.0 $N.mm^{-2}$ (except for 40% turkey oak content, where it is 13.7 $N.mm^{-2}$), while the MOR for 100% aspen composition is 14.0 $N.mm^{-2}$. For all percentage of layered inclusion turkey oak particle, the boards meet the EN 312 standard requirements for P2 and P3 types (EN 312, 2010) (excluding board TO40A60) in terms for the MOR threshold.

For all percentages of layered inclusion of turkey oak particles, the modulus of elasticity of aspen particleboards showed high values, ranging from 2129 $N.mm^{-2}$ to 2379 $N.mm^{-2}$, all of which met the requirements of EN 312 for types P2, P3 and P4 (except for TO10A90 and TO20A80 boards). The study by Tayo Tene *et al.* (Tayo Tene *et al.* 2020) found lower modulus values of 2035 $N.mm^{-2}$ and 2190 $N.mm^{-2}$ for particleboards made from black locust (*Robinia pseudoacacia* L.) using two types of urea-formaldehyde resin.

Similar results were reported by Nelis and Mai (Nelis and Mai 2019), who produced particleboards with a density of 650 $kg \cdot m^{-3}$, with a face layer made of beech particles. According to Nelis and Mai, densification of the face layer leads to more effective adhesive utilization, as the glue is compacted and the particles are brought closer together. This effect outweighs the lower density of paulownia wood particles used in the core layer of their boards. A possible reason for this is the simultaneous impact of multiple factors, where some improve and others reduce the mechanical properties.

The results presented in graphical forming Figure 4 show that as the layered inclusion of turkey oak particles increases from 10% to 50%, the maximum density of the face layers decreases from 926 $kg \cdot m^{-3}$ to 848 $kg \cdot m^{-3}$. According to studies conducted by Laskowska, Wong, Korai and Korai and Miyatake (Laskowska 2024, Wong 1999, Korai 2022, Korai and Miyatake 2023), an increase in the maximum density of the face layer leads to a rise in the modulus of rupture and modulus of elasticity of three-layer particleboards. Increasing the proportion of turkey oak particles, accompanied by a decrease in the proportion of aspen particles, reduces the pressure exerted by the core layer on the face layer, leading to lower compaction and a decrease in the maximum density value of the face layer.

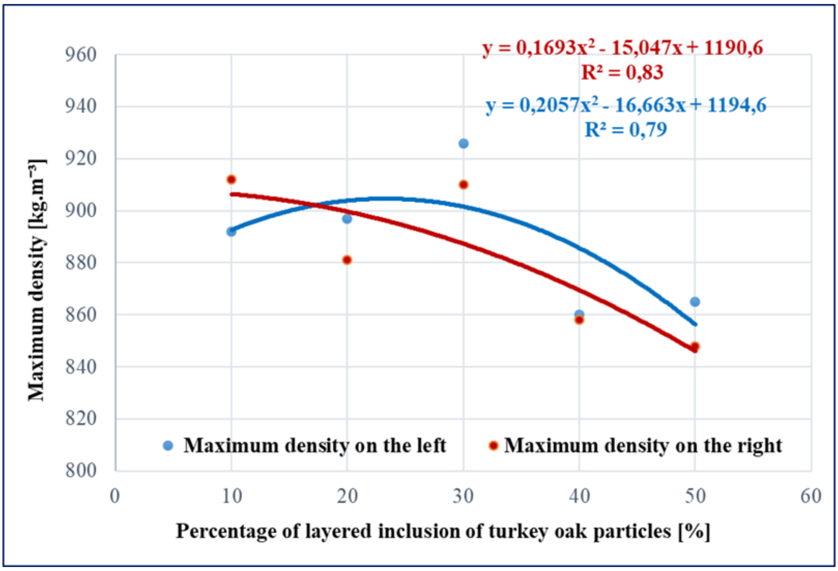

Figure 4: **Maximum density profile of three-layer aspen particleboards with different percentage of layered inclusion of turkey oak particles.**

As a direct consequence of the decreasing maximum density of the face layers, there is also a decrease in the wood compaction ratio, as shown in Figure 5. At 10% turkey oak particle inclusion, the maximum wood compaction ratio drops from 1.12 to 1.04 (at 50% turkey oak particle inclusion), which negatively affects the mechanical strength of the aspen particleboards.

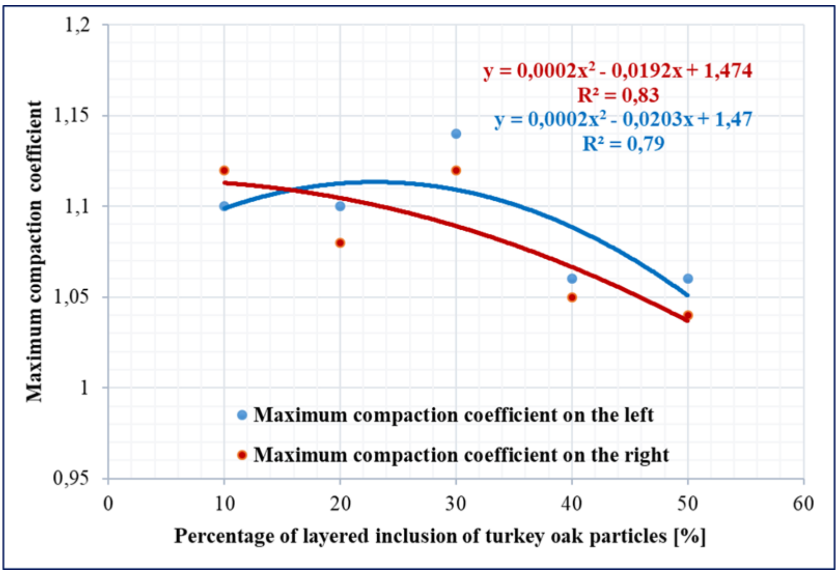

Figure 5: **Maximum compaction ratio of three-layer aspen particleboards with different percentage of layered inclusion of turkey oak particles.**

Increasing the layered inclusion of turkey oak particles in the composition of aspen boards from 10% to 50% does not affect the MOR and MOE values. This fact is quite interesting, and the likely reason lies in the involvement of several factors. First, in the surface zone of the face layer, the turkey oak particles are over-compacted at 10% oak inclusion (compaction ratio – 1.12), at 20% inclusion – 1.1, and at 30% inclusion – 1.14 (as shown in Figure 5). In this way, the oak wood, which has high mechanical strength, enhances the MOR and MOE. However, the graph in Figure 5 shows that the compaction ratio decreases, and correspondingly, the influence of turkey oak particles in the face layer also decreases.

At 40% and 50% layered inclusion of turkey oak particles, it is evident that the compaction ratio remains constant – around 1.06. Here, a second factor likely comes into play – the size of the oak particles in the core layer. The wood particles in the core layer are larger and longer than those in the face layer, which means that the wood fibers in them are significantly longer than those of the face particles. According to the study by Korai (Korai 2022), larger and longer wood particles (core layer particles) indicate that the wood fibers in them are significantly longer than those in the face layer particles. Longer wood fibers can absorb greater tensile stresses in the structure of the particleboard and elongate more under loading compared to the shorter fibers in the face layer. Thus, the two layers of turkey oak particles in the core layer compensate for the reduced degree of densification in the face layers.

A third factor should also be taken into account – the density of the turkey oak particles. The layered inclusion of turkey oak particles in the core layer replaced the aspen particle layers. However, at equal weight, the number of aspen particles would be higher (more than twice) than that of turkey oak particles (assuming the particles are of the same size). During the adhesive application process, the turkey oak particles receive more glue on their surface than the aspen ones, because they are nearly half less as numerous (due to the density of aspen – 380 kg·m^{-3} and turkey oak – 810 kg·m^{-3}). This likely contributes to the formation of more adhesive bonds between the turkey oak particles in the core layer, thereby maintaining the MOR and MOE high values of the produced particleboards.

3.5. INTERNAL BOND

The analysis of variance (Table 4) showed that there was no statistically significant difference in the internal bond values of the examined boards. The obtained internal bond values ranged from 0.48 N.mm^{-2} to 0.55 N.mm^{-2} and met the requirements of the EN 312 standard for P2-type boards. These values were higher than those of the reference board and the board made with 100% aspen particles. Similar values were reported by Eslah (Eslah *et al.* 2012), who obtained an internal bond of 0.57 N.mm^{-2} for single-layer poplar boards with a density of 623 kg·m^{-3} and 8% binder content. The internal bond was strongly influenced by the density of the particleboard, as was confirmed by Wong, Esteves *et al.* and Kalaycioglu *et al.* (Wong 1999, Esteves *et al.* 2023, Kalaycioglu *et al.* 2005). Therefore, the varying layer proportions of turkey oak particles did not affect this property. Based on the results presented in Table 6 for the central density of the core layer of aspen particleboards, it was observed that the density of the core layer varied within very narrow limits-from 524 kg·m^{-3} to 555 kg·m^{-3}-which indicated that the different percentages of layered inclusion of turkey oak particles did not negatively affect the density of the core layer.

3.6. SURFACE SOUNDNESS

Increasing the percentage of layered inclusion of turkey oak particles from 10% to 50% led to an increase in the surface soundness of three-layered aspen particle boards. A minimum surface soundness value of 0.89 N.mm^{-2} was recorded at 10% layered participation of turkey oak, and a maximum value of 1.2 N.mm^{-2} was recorded at 30% layered participation of turkey oak. The increase in surface soundness values was due to the higher proportion of turkey oak particles, which received more glue on their surface compared to aspen particles, resulting in more adhesive bonds between the particles. The determined surface soundness values met the requirements of the EN 312 standard for type P2 boards.

CONCLUSIONS

Increasing the percentage of layered inclusion of turkey oak particles from 10% to 50% in the composition of three-layer aspen particle boards from the face layers to the intermediate layer does not lead to a decrease in the values of the modulus of rupture and the modulus of elasticity. The values of the modulus of rupture and the modulus of elasticity remain at a constant level.

By layering turkey oak particles in the composition of three-layer aspen particleboards from the surface of the face layer to the interior of the core layer, a maximum hardwood content of 50% can be achieved in the composition of medium-heavy particleboards without negatively affecting the values of their physical and mechanical indicators.

DECLARATION OF INTEREST:

The author reports no potential conflicts of interest.

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