Effect of Wood Species, Bark Particle Size, and Adhesive Type on the Properties of Bark-Based Boards

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Significant quantities of bark are generated during wood processing, with the majority being utilized for energy production and soil enhancement. This study investigated the influence of bark particle size and resin type (urea-formaldehyde (UF) and melamine-urea-formaldehyde (MUF)) on the properties of particleboards made from spruce and pine bark. Board samples were fabricated using different bark particle sizes (2 to 5 mm and 5 to 8 mm) and varying adhesive contents (5% and 7%) for both UF and MUF adhesives. Reference particleboards were manufactured using industrial wood particles with the same UF and MUF adhesive contents. The spruce bark consistently outperformed pine bark across most investigated properties. Board samples fabricated from spruce bark particles exhibited higher internal bond (IB) strength and modulus of rupture (MOR), as well as enhanced resistance to water absorption (WA) and thickness swelling (TS), particularly when bonded with urea-formaldehyde (UF) adhesive. Specifically, boards composed of spruce bark, using a combination of bark particle sizes, UF adhesive, and 7% adhesive content, exhibited superior performance in IB strength, water resistance, and modulus of elasticity.

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Keywords: Spruce and pine bark-based panels; Particle size; Urea-formaldehyde adhesive; Melamine-urea-formaldehyde adhesive; Mechanical properties; Physical properties

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INTRODUCTION

Bark is one of the most common by-products generated by the forest industry, sawmilling industry, wood-based panel industry, and paper industry. In the Czech Republic, 13.75 million m^3 of spruce wood (without bark) and 2.03 million m^3 of pine wood (without bark) were harvested in 2023 (Czech Statistical Office 2024). The proportion of bark on sawn timber with a diameter of 15 to 30 cm was 10% for spruce logs and 17% for pine logs (Harkin and Rowe 1971; Čunderlík 2009), which resulted in 1.37 million m^3 of spruce bark and 345 thousand m^3 of pine bark. This amount of bark has been mainly used recently for energy purposes and soil improvement. A more efficient utilization of bark could create a new industry and boost the economy by transforming a residual material into a valuable resource: a raw material for producing water-resistant, thermal, and sound insulation boards.

Chemically, bark is rich in compounds such as lignin, hemicellulose, tannins, and suberin, exhibiting significant variability depending on species, tree age, and growth conditions. Bark contains less cellulose than wood, with levels ranging from 18 to 25% in the inner bark to 3 to 17% in the outer bark (Ugolev 1986). Hemicellulose content, comprising polysaccharides such as xylose, arabinose, and galactose, constitutes 44.1 to 47.6% of the bark. Lignin, the second most abundant component, exceeds 20% in the outer bark (Deineko and Faustová 2015). Inorganic materials, including ash, are present in higher concentrations in bark compared to wood, with willow bark containing 3.8 to 4.7% ash versus 0.6 to 1.1% in its wood (Shin and Han 2014). These unique properties make bark particularly attractive for insulating and particleboard applications, despite its lower fiber content and slightly reduced mechanical strength compared to wood (Martin 1970). Bark is studied for its natural phenolic content, making it a filler in adhesives (Aydin *et al.* 2017). Tannins from bark are vital for plywood and particleboard adhesives (Hall *et al.* 1960; Anderson *et al.* 1961). Beech bark absorbs formaldehyde, and adding bark flour to urea-formaldehyde (UF) resin enhances reactivity (Bekhta *et al.* 2021). Réh *et al*. (2019) analyzed the effects of beech bark filler on plywood's pressing process and formaldehyde emissions. The development of cold-setting, water-resistant adhesives from fir bark exemplifies the innovative use of bark compounds (Herrick and Conca 1960).

In particleboard production, adhesives play a critical role in determining the final properties of the material. UF and melamine-urea-formaldehyde (MUF) resins are among the most used adhesives, valued for their cost-effectiveness and versatile performance characteristics (Dunky 2003). UF adhesives are particularly popular due to their low cost, ease of application, and strong bonding capability under standard processing conditions. However, their performance is limited in terms of moisture resistance, which makes them less suitable for applications in which they can be exposed to high humidity or water. On the other hand, MUF adhesives provide superior water resistance and durability, which make them more appropriate for applications requiring enhanced mechanical properties and environmental resilience. This difference in performance characteristics has driven the use of MUF adhesives in products designed for outdoor use or in humid environments (Hse *et al.* 2008; Mantanis *et al.* 2018).

Bark-based panels bonded with formaldehyde-based adhesives have been extensively investigated. Rishel *et al*. (1980) examined bark panels made from bark particles passing through a 6.35 mm screen but retained on a 1.52 mm screen, sourced from soft maple, red oak, white oak, black cherry, beech, and yellow-poplar, and bonded with 6% powdered phenol-formaldehyde (PF) resin. They concluded that the bending properties were influenced not only by species but also by density and specimen thickness. However, this relationship was not consistent across all species. Muszynski and McNatt (1984) assessed particleboards incorporating spruce bark particles (2 to 8 mm) in proportions of 0 to 100%, bonded with 12% UF resin. Single-layer boards (19 mm thickness, 634 kg/m³) indicated that increasing bark content reduced mechanical properties due to the lower strength of bark compared to wood. Blanchet *et al.* (2000) produced three-layer particleboards (750 kg/m³) with bark particles (0.02 to 2.5 mm for surface layers, 2.5 to 6 mm for the core), bonded with UF resin (12 to 16% in surface layers, 8% in the core). Pressed at 200°C for 5 min, the boards demonstrated technical feasibility for incorporating bark residues. A follow-up study (Blanchet *et al.* 2008) included melamine overlay-treated boards with refined bark fibers and varied pressing times (2 to 5 min). Papadopoulos (2006) produced single-layer boards (17.5 mm, 750 kg/m³) using 1 to 5 mm spruce bark particles and 5% EMDI resin, achieving stable mechanical properties across bark content ranging from 25% to 100%. Pedieu *et al.* (2008) tested three-layer boards with surface layers made from untreated or 1% NaOH-treated white birch bark particles (0.25 to 1.0 mm), bonded with 5 to 8% PF resin. They demonstrated that panels could be manufactured using up to 45% of the proposed substitute material while still meeting the required mechanical and physical properties. Among the panels, the one with untreated bark particles in the surface layers, bonded with 5% PF resin, was selected as the best, particularly with regard to dimensional stability. Yemele *et al.* (2008) evaluated black spruce and trembling aspen bark particles (0.2 to 7.0 mm) for particleboards bonded with PF resin (3 to 12%). The boards, with targeted densities of 800 kg/m³, indicated strong correlations between particle size, resin content, and mechanical properties. Medved *et al.* (2019) focused on single-layer particleboards incorporating pine bark dust (0.237 mm) at wood-to-bark dust ratios of 90:10, bonded with 11% MUF resin. The panels, with a density of 600 kg/m³, demonstrated that fine bark particles could enhance board properties under controlled conditions. While most bark panels were produced by adding resin, several authors (Burrows 1960; Gao *et al.* 2011; Gupta *et al.* 2011; Wenig *et al.* 2023) have demonstrated that it is possible to produce resin-free bark particleboards by activating the natural gluing capability of the material by hot-pressing the bark. Additionally, recent studies have investigated the formaldehyde-binding capacities of bark boards (Barbu *et al.* 2020) and the production of adhesive-free, low-density insulation panels using spruce bark (Gößwald *et al.* 2021).

This work builds upon and diverges from previous studies by emphasizing the optimization of particle size and adhesive combinations for bark panels, while incorporating bark from spruce and pine, two species not extensively analyzed together in prior research. Studies such as those by Burrows (1960) and Muszynski and McNatt (1984) primarily focused on individual bark types or simplified pressing techniques, whereas this study explores a wider range of controlled variables, including particle size, adhesive content, and resin type. Unlike Gupta *et al.* (2011), which concentrated on thermal pressing and coarse particles, this work examines finer particle fractions in tandem with industrially relevant adhesives. Furthermore, the use of mixed bark and wood fractions extends findings from Blanchet *et al.* (2000) by exploring blends tailored for specific mechanical properties, with recommendations for sustainable industrial applications. Typically, researchers have focused their studies on bark from a single wood species or a single adhesive type (*e.g.*, UF, PF, or EMDI etc.).

This study aimed to expand understanding of the production of bark-based boards, with a particular focus on utilizing bark from the two most commonly harvested tree species in the Czech Republic: spruce and pine. The objectives of the study were to investigate the effects of bark particle size fractions (2 to 5 mm and 5 to 8 mm) from these wood species, as well as the influence of different adhesive types (UF and MUF) and adhesive contents (5% and 7%) on board performance, including internal bond strength, water resistance, and bending properties. Additionally, the study explored the potential of blending bark particles with industrial wood particles to enhance sustainability while preserving mechanical performance. A comparative analysis of the properties of bark-based boards versus reference particleboards made from industrial wood particles was also conducted.

EXPERIMENTAL

Materials

The chips of spruce (*Picea abies*) and pine (*Pinus sylvestris*) bark were obtained from a local company (ALFA Plywood, a.s., Solnice, Czech Republic). Urea-formaldehyde (UF - PREFERE^{TM} 11F304) and melamine-urea-formaldehyde (MUF – SILEKOL 310) resin, as well as commercial spruce core particles with particle sizes 0.2 to 5.0 mm for the reference boards (Fig. 1), were provided by the DDL Lukavec (Czech Republic). The chips, with an initial moisture content (MC) of 25 to 30%, were plasticized by heating in a water bath at 50 °C for 72 h. Due to plasticization, the MC of the bark chips increased to 70 to 80%, resulting in a reduction of dust particles and an increase in the volume of bark chips with larger dimensions. The plasticized bark chips were disintegrated into particles on knife ring flaker MRZ/MSF 1400 (Dieffenbacher GmbH Maschinen- und Anlagenbau, Germany). The bark particles were dried at 70 ± 2 °C for 72 h until a MC of 5.1 ± 0.8% was attained. The dried spruce (Fig. 2) and pine (Fig. 3) bark particles were sieved into fractions with particle sizes of 2 to 5 mm and 5 to 8 mm. Particles smaller than 2 mm were removed, while particles larger than 8 mm were disintegrated and re-sieved.

Fig. 1. Wood particles

Fig. 2. Spruce bark particles 2 to 5 mm (left) and 5 to 8 mm (right)

Fig. 3. Pine bark particles 2 to 5 mm (left) and 5 to 8 mm (right)

The UF resin with a density 1.29 g/cm^3, solid content 66%, viscosity 450 to 650 mPa.s and MUF resin with a density 1.27 to 1.3 g/cm^3, solid content 66% and viscosity 250 to 300 mPa.s were employed in the manufacture of the boards.

Methods

The prepared UF resin mixed with 1% of hardener (30% solution of ammonium chloride) and MUF adhesives without hardener was sprayed with a nozzle in a laboratory rotary blender. The particles were sprayed with the adhesives for 3 min, and then the particles were tumbled in the blender for another 3 min, ensuring a uniform application of the adhesive to the particles. The single-layer boards were pressed using adhesive contents of 5% and 7%, based on the oven-dry weight of the particles. The target density of the boards was 620 kg/m^3. The resinated particles were manually formed without orientation into a mold measuring 600 × 450 mm, then pressed to a thickness of 12 mm at 180 °C for 320 seconds. The press closing time was 15 seconds, followed by a pressure 3.5 MPa for 240 seconds. The pressure was then gradually released over 80 seconds before opening the hot press. In total, 16 board variants were manufactured (Table 1). Two panels of each type of board were pressed (Fig. 4).

Table 1. Terminology and Description of the Composition of the Produced Experimental Boards

Sample	Composition of the Particleboards			
	Type of Particles	Particle Size	Volume of Adhesive	Type of Adhesive
RUF5	Native spruce particles	-	5%	UF
RUF7	Native spruce particles	-.	7%	UF
S25UF5	Spruce bark particles	2 - 5	5 %	UF
S58UF5	Spruce bark particles	5 - 8	5%	UF
S25UF7	Spruce bark particles	2 - 5	7%	UF
P25UF5	Pine bark particles	2 - 5	5%	UF
P58UF5	Pine bark particles	5 - 8	5%	UF
P25UF7	Pine bark particles	2 - 5	7%	UF
RMUF5	Native spruce particles	-	5%	MUF
RMUF7	Native spruce particles	-.	7%	MUF
S25MUF5	Spruce bark particles	2 - 5	5 %	MUF
S58MUF5	Spruce bark particles	5 - 8	5%	MUF
S25MUF7	Spruce bark particles	2 - 5	7%	MUF
P25MUF5	Pine bark particles	2 - 5	5%	MUF
P58MUF5	Pine bark particles	5 - 8	5%	MUF
P25MUF7	Pine bark particles	2 - 5	7%	MUF

The pressed boards were cut into test samples (Fig. 5.) designed to measure modulus of rupture (MOR), modulus of elasticity (MOE), density, moisture content (MC), density profile, internal bond (IB) strength, thickness swelling (TS), and water absorption (WA) according to EN standards. The samples were stored in a climate-controlled chamber at 20 °C and a relative humidity of 65%. Three samples with densities close to the average density were selected for the density profile analysis, seven samples for MOR and MOE, eight samples for IB, and six samples for measuring TS and WA.

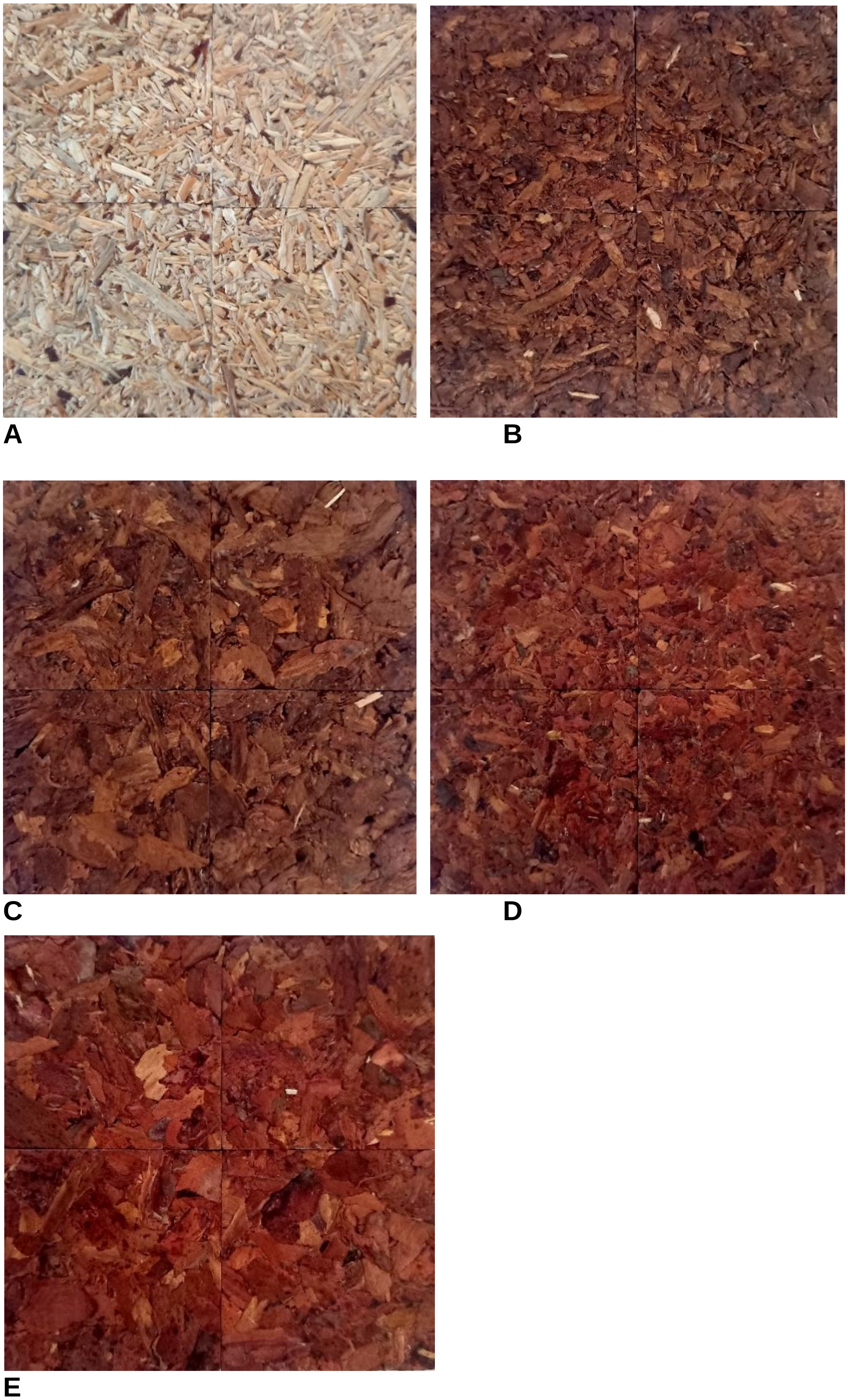

Fig. 4. (A) Reference particleboard made from spruce wood particles, and boards made from (B) spruce bark particles with size 2 to 5 mm, (C) spruce bark particles with size 5 to 8 mm, (D) pine bark particles with size 2 to 5 mm, and (E) pine bark particles with size 5 to 8 mm

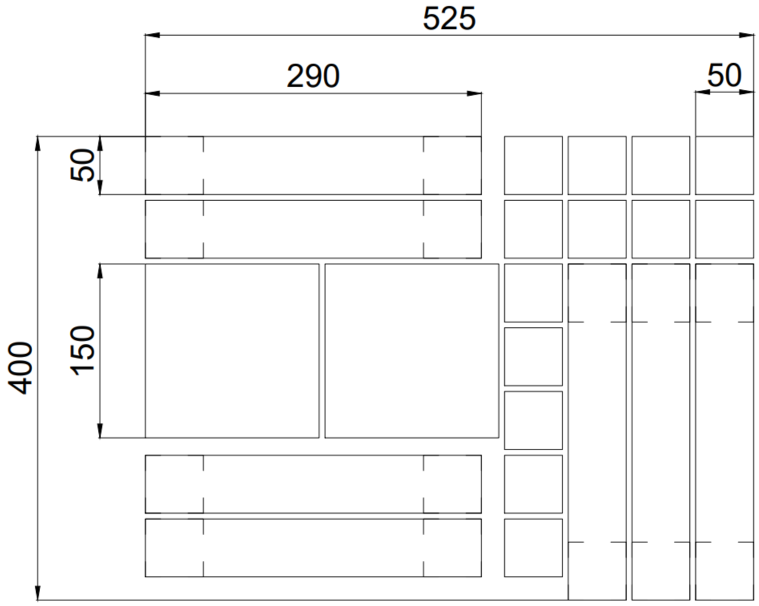

Fig. 5. Cutting plan for test specimen production

Testing of Board Samples

The density was determined according to the methodology outlined in EN 323 (1993) on all samples (50 × 50 mm) from each board. The average density for each variant of the experimental boards was calculated from the densities of all samples. Samples with significant density deviations from the average density were excluded from the analysis.

MC was determined in accordance with the methodology specified in EN 322 (1993) using 20 specimens for each group measuring 50×50 mm^2.

The density profile was assessed using six samples from each group. Samples measuring 50 × 50 × 12 mm^3 were measured at 0.05 mm intervals across the thickness of the samples (12 mm) using compact X-ray Density Profile Analyzer DPX300-LTE (Imal-Pal, Italy).

The TS was determined according to standard EN 317 (1996). The specimens (twelve samples from each group) were submerged in water for specified durations (24, 48, or 168 h). Simultaneously with the measurement of TS, the weight of samples was measured for WA.

The MOR and MOE (10 samples from each group) were determined according to standard EN 310 (1993). IB strength was evaluated by EN 319 (1993) (16 samples from each group) applying a load to the test specimen until it fractured in a direction perpendicular to the plane of the specimen. Mechanical testing was carried out on a Zwick Z050 universal testing machine with testXpert v 11.02 software.

Statistical Analysis

The data were processed in STATISTICA 10 software (StatSoft Inc., USA) and evaluated using a one-factor analysis of variance (ANOVA), completed with Tukey's honest significance test (HSD test) and regression analysis.

RESULTS AND DISCUSSION

Moisture Content and Density of Boards

MC was analyzed through regression, revealing that wood species of bark, particle size, adhesive type (UF or MUF), and adhesive amount (5% or 7%) significantly impacted MC (Table 2). Regression coefficient (R^2) values ranged from 0.34 to 0.52, indicating moderate to good model fit. Tukey's test confirmed significant differences between samples, with wood species being the primary influencing factor. Reference samples had the lowest MC, while samples with bark particles exhibited approximately 20% higher MC. Spruce bark samples had higher MC than pine bark samples, a difference confirmed by Tukey's test, except between S25MUF7 (11.6%) and P25MUF7 (11.4%), where the difference was statistically insignificant. The regression coefficient for wood species was +1.23 ($p < 0.05$). Particle size had a slight but insignificant effect on MC, with smaller particles (2 to 5 mm) generally having lower MC than larger particles (5 to 8 mm), but this difference was not statistically significant. The regression coefficient for particle size was +0.11 ($p = 0.22$). UF adhesive reduced MC (9.6%), particularly in reference samples (RUF7) with 7% adhesive and smaller particle sizes (2 to 5 mm), though these differences were not significant. No synergistic effect was observed between adhesive type and MC of samples, as seen in S25UF7 (11.6%) and S25MUF7 (11.6%). The regression coefficient for the adhesive type was +0.04 ($p = 0.76$), and adhesive amount (5% *vs.* 7%) had no significant impact, except for spruce bark samples (S25UF5 *vs.* S25UF7), where increasing adhesive application reduced moisture absorption. The regression coefficient for the adhesive amount was -0.05 ($p = 0.64$). Overall, wood species was the most significant factor influencing MC, with spruce bark showing higher MC than pine bark. Particle size, adhesive type, and adhesive amount had no significant impact, except for spruce bark, where differences were confirmed by Tukey's test and regression analysis.

Table 2. Average Values of Density and Equilibrium MC of UF- and MUF-Bonded Boards

	Density (kg/m^3)			MC (%)		
RUF5	658	(45)	A, B	9.7	(0.1)	F
RMUF5	658	(20)	A, B	9.7	(0.2)	F
RUF7	662	(30)	A	9.6	(0.1)	F
RMUF7	655	(23)	A, B, C	9.7	(0.1)	F
S25UF5	623	(50)	C, D, E, F	11.9	(0.1)	B
S25MUF5	620	(52)	D, E, F	12.0	(0.1)	A, B
S58UF5	612	(47)	E, F	12.0	(0.1)	A, B
S58MUF5	644	(49)	A, B, C, D, E	12.3	(0.1)	A
P25UF5	646	(61)	A, B, C, D	11.3	(0.1)	D, E
P25MUF5	635	(55)	A, B, C, D, E, F	11.4	(0.1)	C, D, E
P58UF5	613	(40)	D, E, F	11.5	(0.1)	C, D, E
P58MUF5	614	(37)	D, E, F	11.2	(0.1)	E
S25UF7	627	(53)	B, C, D, E, F	11.6	(0.2)	C
S25MUF7	644	(49)	A, B, C, D, E	11.6	(0.2)	C, D
P25UF7	636	(47)	A, B, C, D, E	11.2	(0.2)	E
P25MUF7	600	(57)	F	11.4	(0.1)	C, D, E
Means with the same letter in column do not differ statistically by the Tukey´s test (α=0.05). Number in parentheses represents standard deviation.						

In this study, the MC ranged from 11.2% (P25UF7) to 12.0% (S58UF5). These values were higher compared to data available in the literature. Medved *et al.* (2020) reported MC values for panels made from bark at 5.49% (100% wood particles) and 7.02% (50/50 bark/wood particles), with both results being lower than the values measured in this study. Gupta *et al.* (2011) recorded even lower MC values for panels made from bark particles of different sizes, specifically 1.21% (coarse), 1.29% (medium), 2.2% (fine), and 1.46% (mixed). These results demonstrated a slight increase in the MC as the bark particle size decreased. Medved *et al.* (2019) reported MC values of 9.0% (100% wood particles) and 9.3% (90/10 wood/bark particles), which were closer to the values obtained in this study but still lower. Therefore, the MC values measured in this study were higher than those reported by Medved *et al.* (2019, 2020) and Gupta *et al.* (2011), as these authors used bark particles with lower MC and pressed the boards at higher temperatures than in the present study. For example, the lower MC values observed in the boards produced by Gupta *et al.* (2011) can be attributed to the use of bark particles with a lower MC of 2 to 3% and a very high pressing temperature (170 to 230 °C, up to 300 °C). Additionally, the boards were produced without synthetic resins, meaning no extra water was added to the chip mat. Medved *et al.* (2019, 2020) blended 10 to 80% bark particles (with an MC of approximately 2%) with wood particles and pressed the boards at temperatures of 180 to 200 °C.

Regression analysis indicated that the average density of the samples was influenced by wood species, particle size, adhesive type, and adhesive amount. R^2 values ranged from 0.23 to 0.41, suggesting moderate model explanatory capability. Statistically significant differences were confirmed by Tukey’s test only for specific comparisons. Particle size had an insignificant effect on density. Tukey’s test suggested that samples with smaller particles (2 to 5 mm, 641 kg/m³) had a slightly higher density than those with larger particles (5 to 8 mm, 632 kg/m³), but this difference was not statistically significant (-0.89, $p = 0.18$). Wood species of bark significantly impacted density, with S25MUF7 (644 kg/m³) being denser than P25MUF7 (600 kg/m³), a difference confirmed by Tukey’s test. However, no significant density differences were found between other spruce and pine comparisons, such as S25UF7 (627 kg/m³) *vs.* P25UF7 (636 kg/m³). Adhesive type (UF *vs.* MUF) also significantly affected density, with P25UF7 (636 kg/m³) being denser than P25MUF7 (600 kg/m³), as confirmed by Tukey's test. For other comparisons, differences between UF and MUF adhesives were observed but were not statistically significant. Adhesive amount (5% *vs.* 7%) did not significantly impact density, with reference samples RMUF5 (658 kg/m³) and RMUF7 (655 kg/m³) showing no significant difference according to Tukey’s test. Overall, wood species of bark was the main factor influencing density, while particle size, adhesive type, and adhesive amount had minimal, statistically insignificant effects on density.

The density of panels was identified as one of the key parameters influencing the mechanical properties and stability of the final materials. In this study, the panel density ranged between 600 and 662 kg/m³. These values were comparable to the data reported in the literature, where some studies achieved higher densities due to the use of PF or isocyanate adhesives, higher pressing pressures, or specific board compositions (Rishel *et al.* 1980; Muszynski and McNatt 1984; Blanchet *et al.* 2000; Medved *et al.* 2019, 2020; Papadopulos 2006; Pedieu *et al.* 2008; Yemele *et al.* 2008).

Density Profile

The vertical density profiles (VDPs) of all board samples are shown in Fig. 6. A characteristic feature of these VDPs is their typical "U-shape" (Kelly 1977), where the surface layers exhibited higher density compared to the core layer.

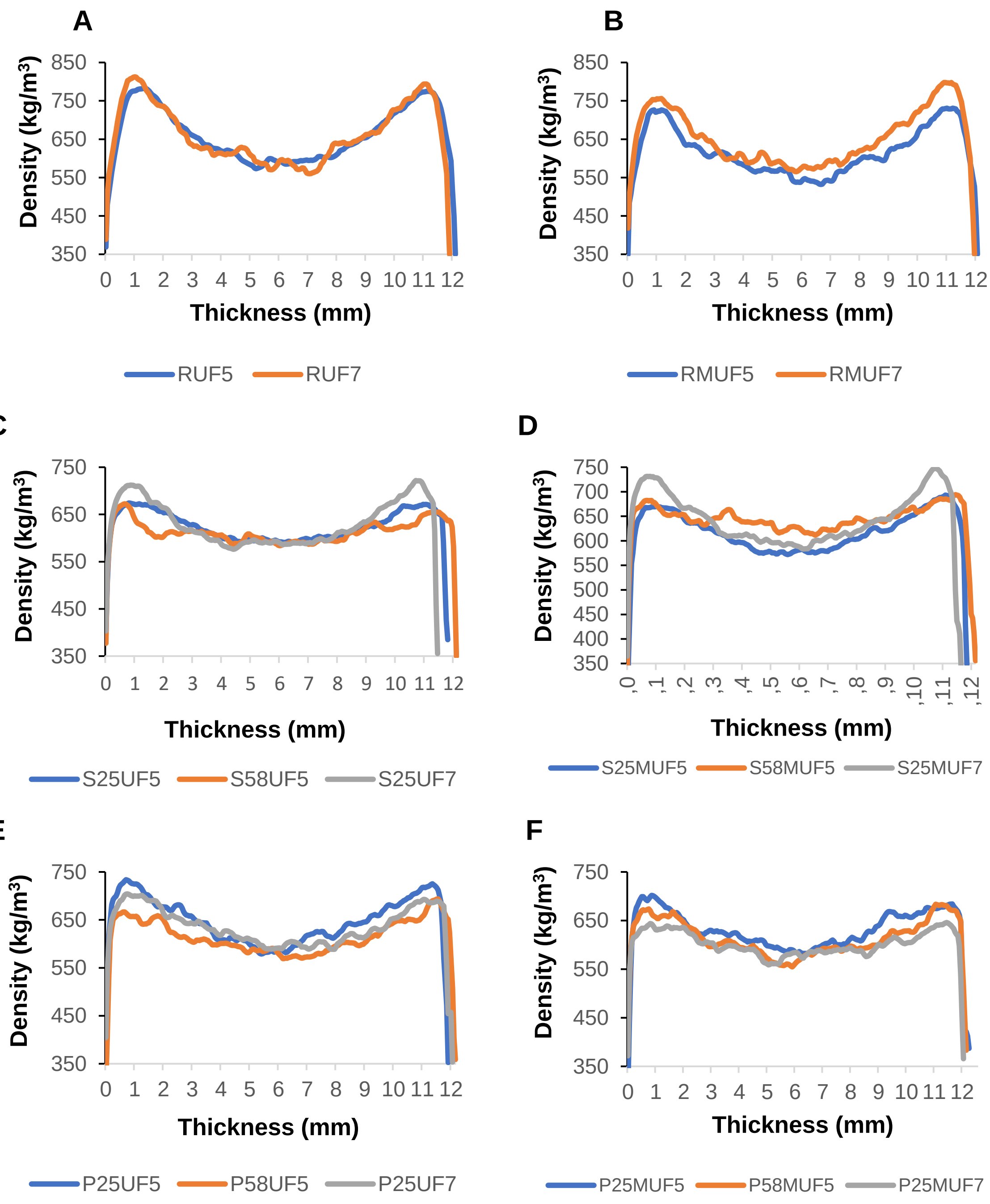

Fig. 6. The density profile of reference particleboards (A, B), spruce (C, D) and pine (E, F) bark boards bonded with UF (A, C, E) and MUF (B, D, F) resin

The average densities of the samples, as described earlier, ranged between 600 and 658 kg/m³, depending on the particle type, adhesive type, and adhesive content. For instance, spruce-based samples (*e.g.*, S25MUF7: 644 kg/m³) exhibited higher average densities than pine-based samples (*e.g.*, P25MUF7: 600 kg/m³), a difference confirmed as statistically significant by Tukey's test. However, for other factors such as particle size or adhesive content, the observed differences in average density were not statistically significant, even though they were visible in the density profiles.

As shown in the graphs, samples without bark particles (RUF5, RUF7) exhibited uniform U-shaped profiles, with higher densities at the surface layers compared to the core. Increasing the adhesive content from 5% (RUF5) to 7% (RUF7) resulted in a slight increase in density across the entire thickness of the samples.

For samples containing bark particles, such as spruce-based (S25UF7, S25MUF7) and pine-based (P25UF5, P25MUF5), the density profiles also followed a U-shaped trend, but with generally lower surface and core densities compared to bark-free samples. These differences in density were influenced by the particle type, with spruce-based boards achieving higher densities than pine-based boards. However, within these samples, the density differences between the surface and core layers were smaller compared to reference particleboard (RUF5, RUF7).

The type of adhesive also affected the density profiles. MUF-bonded samples (*e.g.*, RMUF5, RMUF7) exhibited slightly higher densities, particularly in the surface layers, than UF-bonded samples (*e.g.*, RUF5, RUF7). While this trend was visible in the density profiles, the differences in average densities between UF and MUF adhesives were not statistically significant.

In summary, the graphs highlight distinct variations in density between the surface and core layers of the samples, following the typical U-shaped trend. However, the statistical analysis indicates that many of these differences, particularly those related to particle size, adhesive content, and adhesive type, were not significant. The most pronounced and statistically significant factor affecting density was the particle type, with spruce particles producing denser boards compared to pine particles.

Thickness Swelling

Figures 7 and 8 illustrate the TS of UF- and MUF-bonded boards.

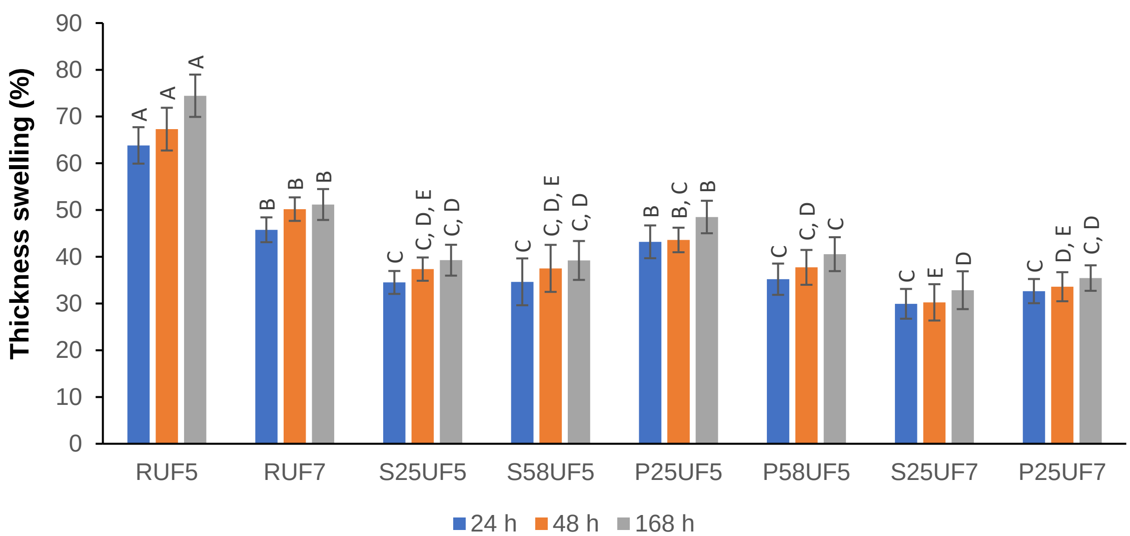

Fig. 7. Thickness swelling of UF-bonded specimens after varying duration of water immersion (letters above the error bars that are the same do not have a statistically significant difference by the Tukey's test α = 0.05)

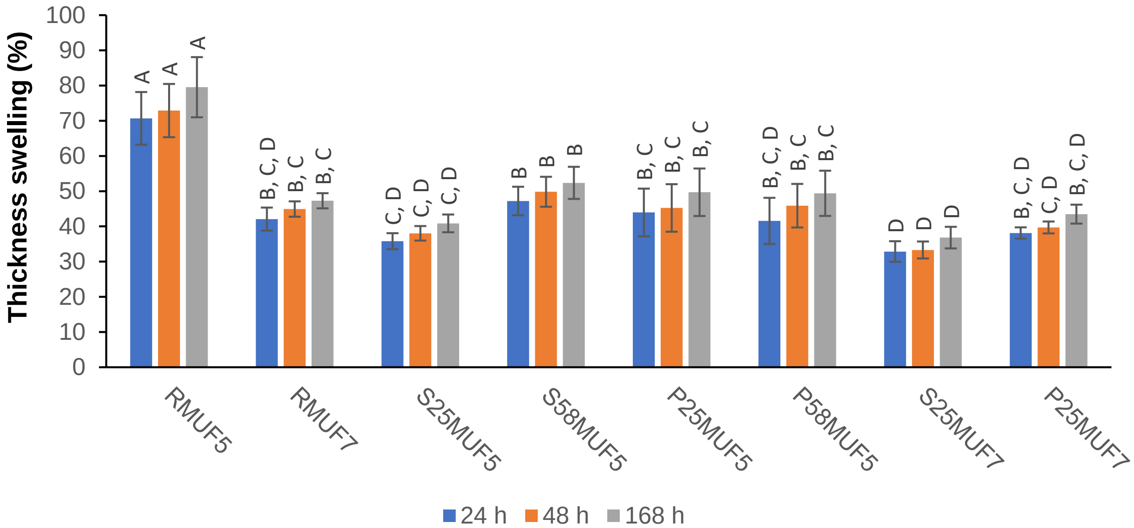

Fig. 8. Thickness swelling of MUF-bonded specimens after varying duration of water immersion (letters above the error bars that are the same do not have a statistically significant difference by the Tukey´s test α = 0.05)

Regression analysis revealed that all models for TS demonstrated strong explanatory capability, with R^2 values ranging from 0.71 (24 h) to 0.75 (168 h). The factors of wood species of bark, particle size, adhesive type, and adhesive amount were all statistically significant for TS and WA, with consistent results across different time intervals.

Wood species of bark (spruce vs. pine)

Spruce bark samples demonstrated greater resistance to swelling compared to pine bark samples. However, no statistically significant differences were found between the following pairs: S58MUF5 *vs.* P58MUF5 and S25UF5 *vs.* P25UF5 after the various soaking intervals (24, 48, and 168 h). The highest swelling resistance in spruce bark samples was observed in S25MUF5 (35.8%/24h, 38%/48h, 40.9%/168h).

Particle size

Samples made from spruce bark with smaller particle sizes (2 to 5 mm) and bonded with 5% UF adhesive swelled less after 24 h (34.5%) and 48 h (37.4%) compared to those with larger particle sizes (5 to 8 mm), although these differences were not statistically significant according to Tukey’s test. Similarly, pine bark samples showed better resistance to swelling, with P58MUF5 exhibiting higher swelling than P25MUF5, but no statistically significant differences were found.

Adhesive type (UF vs. MUF)

UF adhesive showed better swelling resistance (lower TS) than MUF adhesive for all samples, including reference, spruce, and pine bark samples, across all time intervals. Statistically significant differences were observed in reference samples and pine bark samples bonded with UF adhesive (*e.g.*, P25UF5 *vs*. P25UF7).

Adhesive amount (5% vs. 7%)

Increasing the adhesive amount to 7% increased the swelling resistance of all samples, with a notable reduction in TS across all time intervals. Statistically significant differences were found only for reference samples and pine bark samples bonded with UF adhesive (P25UF5 *vs*. P25UF7), showing better performance with higher adhesive amounts. For example, the TS of reference samples RUF5 (63.8%/24h, 67.3%/48h, 74.4%/168h) was significantly higher than RUF7 (45.8%/24h, 50.2%/48h, 51.2%/168h). In conclusion, the following observations can be summarized: spruce bark generally exhibited better swelling resistance than pine bark; UF adhesive resulted in lower swelling compared to MUF adhesive across all samples; and an increase in adhesive amount to 7% enhanced swelling resistance, with significant differences primarily observed in reference and pine bark samples.

In this study, TS values ranged from 30% (S25UF7) to 35% (P58UF5), and 33% (S25MUF7) to 47% (S58MUF5) for 24 h, with these results differing significantly from the data available in the literature. These values (Table 3) were higher compared to the results of Pedieu *et al.* (2008) and Papadopoulos (2006), who achieved low values due to the use of stabilizing adhesives. In contrast, the results from Medved *et al.* (2020) were significantly higher and demonstrated the limitations of panels with high bark content. The findings of this study were partially comparable to the data reported by Gupta *et al.* (2011), Medved *et al.* (2019), and Blanchet *et al.* (2000), which showed the influence of particle fraction and resin content on panel stability.

Water Absorption

The WA of UF- and MUF-bonded samples is shown in Figs. 9 and 10. Regression analysis showed that wood species of bark, particle size, adhesive type, and adhesive amount all influenced WA resistance, with wood species of bark having the most significant effect.

Particle size

Spruce bark samples with smaller particle sizes (2 to 5 mm), bonded with 5% UF and MUF adhesives, absorbed less water than those with larger particle sizes (5 to 8 mm). Pine bark samples showed the opposite trend, with smaller particles absorbing more water than larger particles. However, Tukey's test did not find particle size differences to be statistically significant for WA.

Wood species of bark (spruce vs. pine)

Pine bark samples exhibited higher resistance to WA than spruce bark samples, especially for larger particle sizes (*e.g.*, P58UF5 *vs.* S58UF5). Statistically significant differences were observed in pine bark samples (*e.g.*, P25UF5 *vs.* S25UF5) and reference samples when bonded with UF adhesive, favoring pine bark for better WA resistance. In some cases (*e.g.*, S25MUF5 *vs.* P25MUF5), the differences were not significant, except for after 168 h, where pine bark showed better performance.

Effect of adhesive type (UF vs. MUF)

UF adhesive generally provided better WA resistance (lower WA) than MUF adhesive across all samples. For reference and pine bark samples, UF adhesive consistently outperformed MUF adhesive, with significant differences observed for reference samples (RUF5 *vs.* RUF7) and pine bark samples (P25UF5 *vs.* P25UF7).

Effect of adhesive amount (5% vs. 7%)

Increasing adhesive amount to 7% improved WA resistance for all samples across the time intervals (24, 48, and 168 h). Statistically significant differences were noted for reference samples (RUF5 *vs.* RUF7, RMUF5 *vs.* RMUF7) and pine bark samples (P25UF5 *vs.* P25UF7), where 7% adhesive resulted in better water resistance. In summary, the following observations can be summarized: pine bark samples generally exhibited better WA resistance than spruce bark samples, especially with UF adhesive; UF adhesive was more effective than MUF adhesive at reducing WA; increasing adhesive amount to 7% improved WA resistance across all sample types, with significant effects observed primarily in reference and pine bark samples.

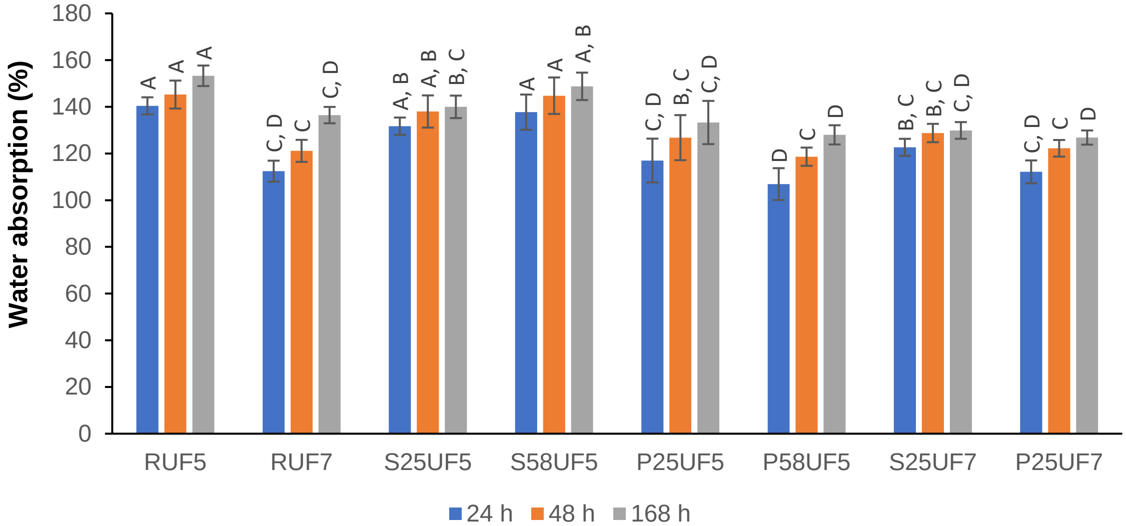

Fig. 9. Water absorption of UF-bonded specimens after varying duration of water immersion (letters above the error bars that are the same do not have a statistically significant difference by the Tukey´s test α = 0.05).

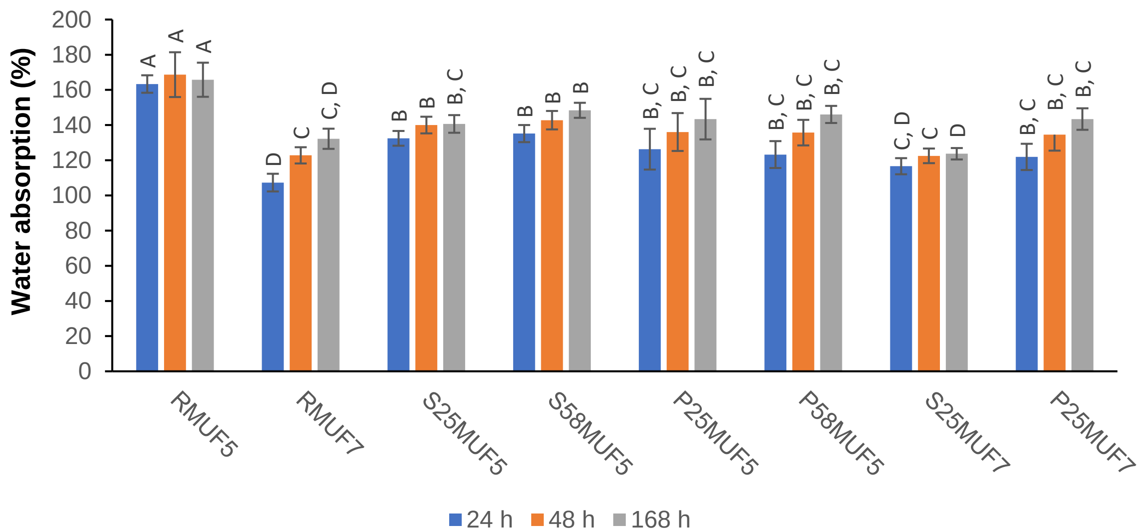

Fig. 10. Water absorption of MUF-bonded specimens after varying duration of water immersion (letters above the error bars that are the same do not have a statistically significant difference by the Tukey´s test α = 0.05).

In this study, WA values after 24 h ranged, for UF-bonded specimens, from 107% (P58UF5) to 138% (S58UF5) and for MUF-bonded specimens from 117% (S25MUF7) to 135% (S58MUF5). These results were partially higher compared to the literature (Table 3) (Burrows 1960; Muszynski and McNatt 1984; Gupta *et al.* 2011), with the differences possibly caused by the panel structure and the type of material used. Similar results were observed by Medved *et al.* (2019), who recorded high WA values after 24 h for panels with varying ratios of bark and wood. Panels made of 100% wood particles exhibited WA of 98%, while the 90/10 (wood/bark particles) samples showed a value of 81.5%. These results demonstrated improved resistance to WA with the increased share of fine (bark) particles in the surface layers of the samples.

Modulus of Rupture

Figures 11 and 12 illustrate the MOR of UF- and MUF-bonded samples. Regression analysis revealed that adhesive type (UF *vs.* MUF) and adhesive amount (5% *vs.* 7%) significantly affected the MOR, with R^2 values ranging from 0.68 to 0.81, indicating high explanatory power. Tukey's test identified statistically significant differences between samples. Reference samples, such as RUF7 (11 MPa), exhibited the highest MOR, while samples with bark particles showed lower values, such as 4.8 MPa for S25MUF7 and 2.1 MPa for P25MUF7.

Particle size

Particle size influenced MOR, with smaller particles (2 to 5 mm) achieving higher MOR values compared to larger particles (5 to 8 mm), but only in MUF-bonded samples. The regression coefficient for particle size was +7.4 ($p < 0.05$).

Wood species of bark (spruce vs. pine)

Wood species of bark also affected MOR, with spruce bark yielding higher MOR values than pine bark, though the differences were not statistically significant. The regression coefficient for wood species of bark was +9.2 ($p < 0.01$).

Effect of adhesive type (UF vs. MUF)

Adhesive type influenced MOR, with MUF-bonded samples generally showing higher MOR values than UF-bonded samples. However, Tukey's test did not find significant differences except in specific samples, such as RUF5 (9.6 MPa). The regression coefficient for adhesive type was +6.5 ($p < 0.01$).

Effect of adhesive amount (5% vs. 7%)

Adhesive amounts also had a significant impact on MOR. Samples with 7% adhesive generally showed higher MOR, with exceptions such as P25MUF5 (2.8 MPa) and P25MUF7 (2.1 MPa), where no significant difference was found. Statistically significant differences were observed primarily in reference samples. The regression coefficient for adhesive amount was +5.3 ($p < 0.05$). In conclusion, a combination of spruce bark, smaller particles, MUF adhesive, and higher adhesive content led to higher MOR values, with significant differences observed only in reference samples with 7% adhesive.

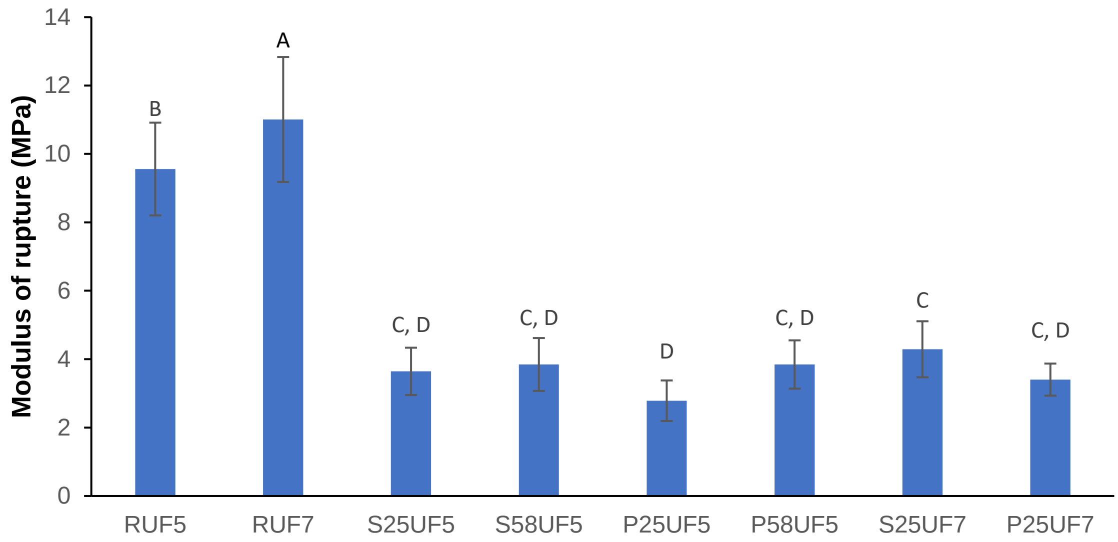

Fig. 11. Modulus of rupture of UF-bonded boards (letters above the error bars that are the same do not have a statistically significant difference by the Tukey´s test α = 0.05**).**

The MOR values ranged from 2.8 MPa (P25UF5) to 4.3 MPa (S25UF7) and from 2.1 MPa (P25MUF7) to 4.8 MPa (S25MUF7), with differences between samples being related to the material used and its structure. Comparisons with the literature (Table 3) demonstrated varying strength levels depending on the type of material, pressing conditions, and additional components (Rishel *et al.* 1980; Muszynski and McNatt 1984; Blanchet *et al.* 2000; Papadopulos 2006; Yemele *et al.* 2008; Medved *et al.* 2020).

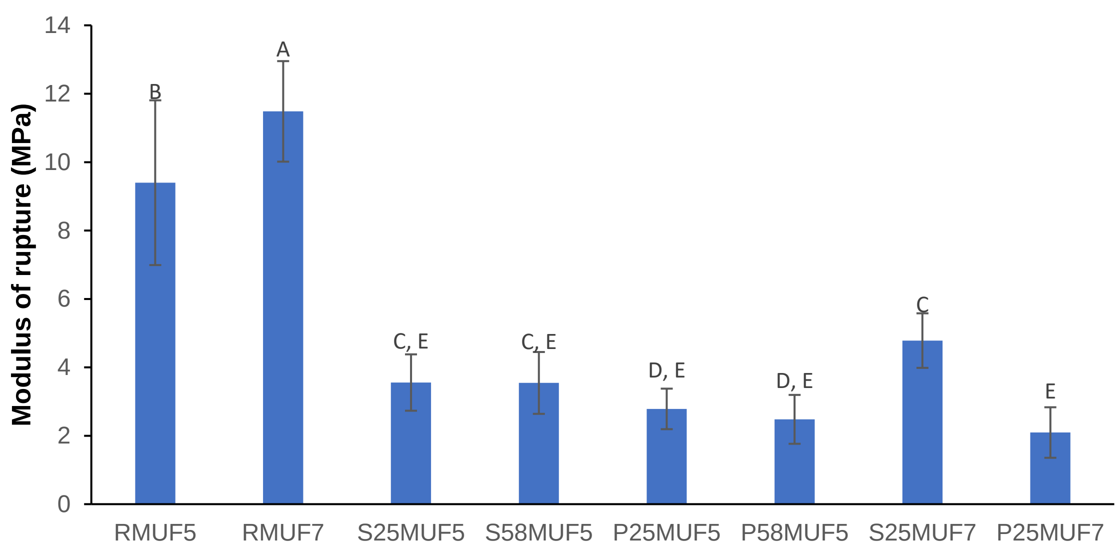

Fig. 12. Modulus of rupture of MUF-bonded boards (letters above the error bars that are the same do not have a statistically significant difference by the Tukey´s test α = 0.05)

Modulus of Elasticity

The MOE of UF- and MUF-bonded samples is shown in Figs. 13 and 14. Regression analysis demonstrated that wood species of bark, particle size, adhesive type (UF *vs*. MUF), and adhesive amount (5% *vs*. 7%) influenced the MOE of the samples. R^2 values ranged from 0.72 to 0.85, indicating excellent model explanatory capability.

Reference samples, such as RMUF7, exhibited the highest average MOE (2559 MPa), while bark-containing samples, like S25UF5 (737 MPa) and P25UF5 (740 MPa), showed lower values.

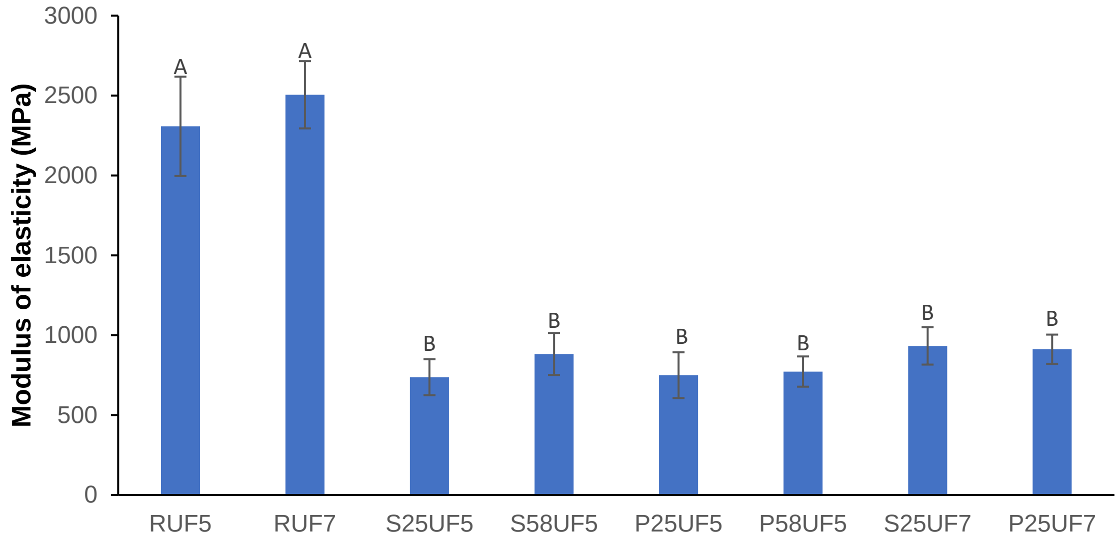

Fig. 13. Modulus of elasticity of UF-bonded boards (letters above the error bars that are the same do not have a statistically significant difference by the Tukey´s test α = 0.05).

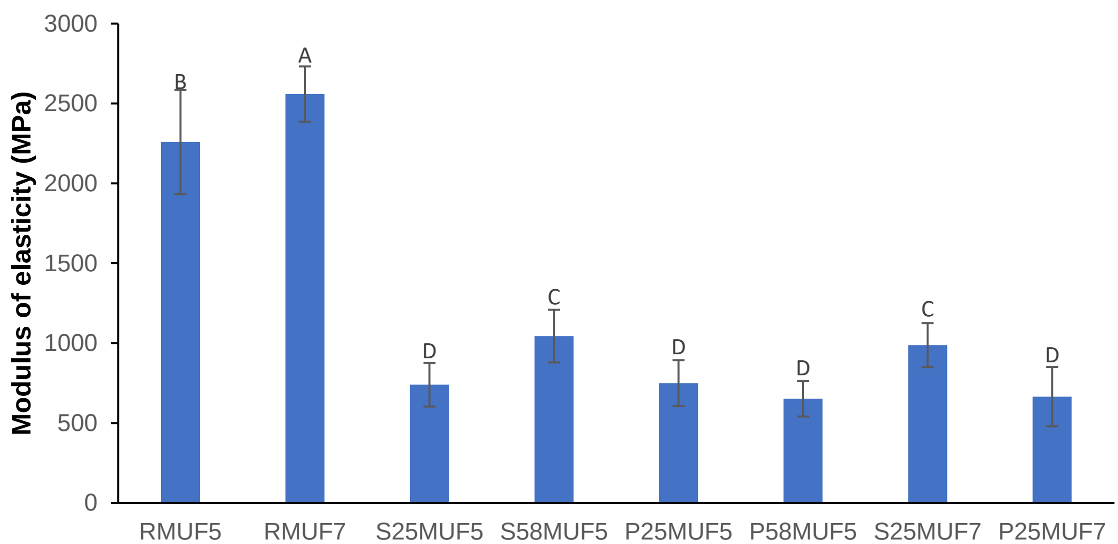

Fig. 14. Modulus of elasticity of MUF-bonded boards (letters above the error bars that are the same do not have a statistically significant difference by the Tukey´s test α = 0.05)

Particle size

Particle size affected MOE, with smaller particles (2 to 5 mm) generally exhibiting lower MOE than larger particles (5 to 8 mm), except for pine bark samples bonded with MUF adhesive, where smaller particles (P25MUF5: 750 MPa) had higher elasticity than larger ones (P58MUF5: 652 MPa), though the difference was not statistically significant. However, a significant difference was observed between S25MUF5 (740 MPa) and

S58MUF5 (1044 MPa), with the regression coefficient for particle size determined to be +700 ($p < 0.05$).

Wood species of bark (spruce vs. pine)

Wood species of bark significantly influenced MOE, with spruce bark particles exhibiting higher MOE than pine bark particles. Statistically significant differences were confirmed between spruce and pine samples bonded with MUF resin, such as S58MUF5 (1044 MPa) *vs.* P58MUF5 (652 MPa) and S25MUF7 (987 MPa) *vs.* P25MUF7 (665 MPa). The regression coefficient for particle type was +860 ($p < 0.01$).

Effect of adhesive type (UF vs. MUF)

The type of adhesive used had no significant impact on MOE in most samples. However, Tukey's test revealed significant differences in certain samples, such as S58MUF5 (1044 MPa) *vs.* S58UF5 (883 MPa) and P25UF7 (913 MPa) *vs.* P25MUF7 (665 MPa).

Effect of adhesive amount (5% vs. 7%)

The adhesive amount had a significant impact on MOE for some samples. Samples with 7% adhesive generally showed higher MOE, except for P25MUF5 (750 MPa) and P25MUF7 (665 MPa), where no significant difference was found. Statistically significant differences were confirmed for reference samples and spruce bark samples bonded with MUF adhesive. The regression coefficient for adhesive amount was +450 ($p < 0.05$).

The MOE values ranged from 737 MPa (S25UF5) to 933 MPa (S25UF7) and from 652 MPa (P58MUF5) to 1044 MPa (S58MUF5). These values were comparable to or lower than published results (Table 3) (Rishel *et al.* 1980; Muszynski and McNatt 1984; Blanchet *et al.* 2000; Yemele *et al.* 2008; Medved *et al.* 2020).

Internal Bond Strength

Figures 15 and 16 illustrate the IB strength of UF- and MUF-bonded samples. Regression analysis demonstrated that wood species of bark, particle size, adhesive type (UF *vs.* MUF), and adhesive amount (5% *vs.* 7%) significantly affected IB strength. R^2 values ranged from 0.72 to 0.83, indicating a high explanatory capability. Statistically significant differences between samples were confirmed by Tukey's test. Reference samples, such as RUF7, achieved the highest IB (0.48 MPa), while samples containing bark particles exhibited lower values, with S25UF5 at 0.23 MPa and P25UF5 at 0.08 MPa.

Particle size

Particle size had a significant effect on IB, with a regression coefficient of +0.08 ($p < 0.05$). Higher IB values were observed in samples with 2 to 5 mm particles, but Tukey’s test indicated that size influenced only spruce bark samples, regardless of adhesive type.

Wood species of bark (spruce vs. pine)

The wood species of bark was the most significant factor, with spruce bark showing 52% higher IB than pine bark in S58UF5 *vs.* P58UF5, and 84% higher in S25MUF7 *vs.* P25MUF7. These differences were statistically significant, with a regression coefficient for particle type of +0.12 ($p < 0.01$).

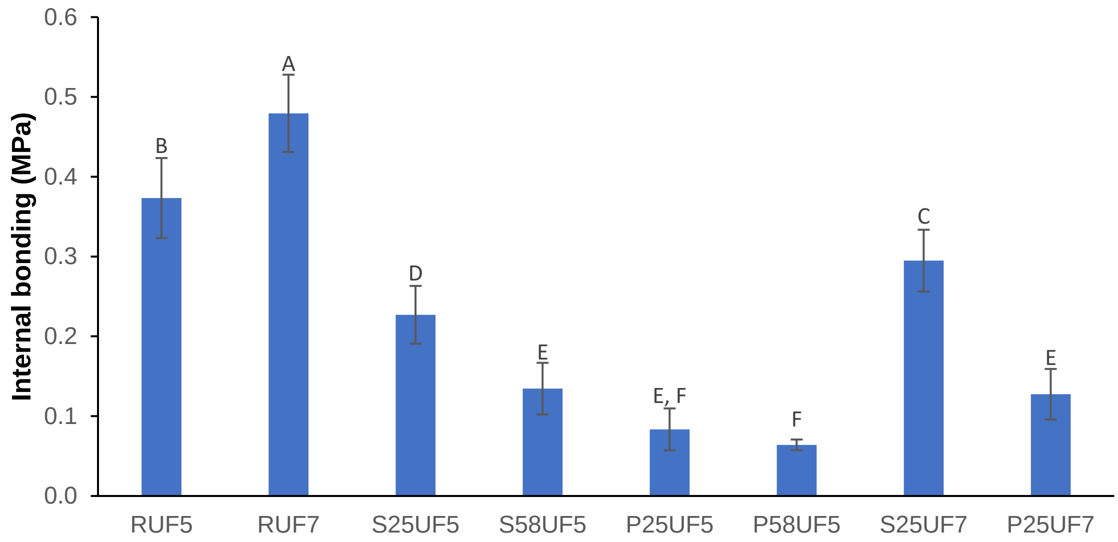

Fig. 15. Internal bond strength of UF-bonded boards (letters above the error bars that are the same do not have a statistically significant difference by the Tukey´s test α = 0.05)

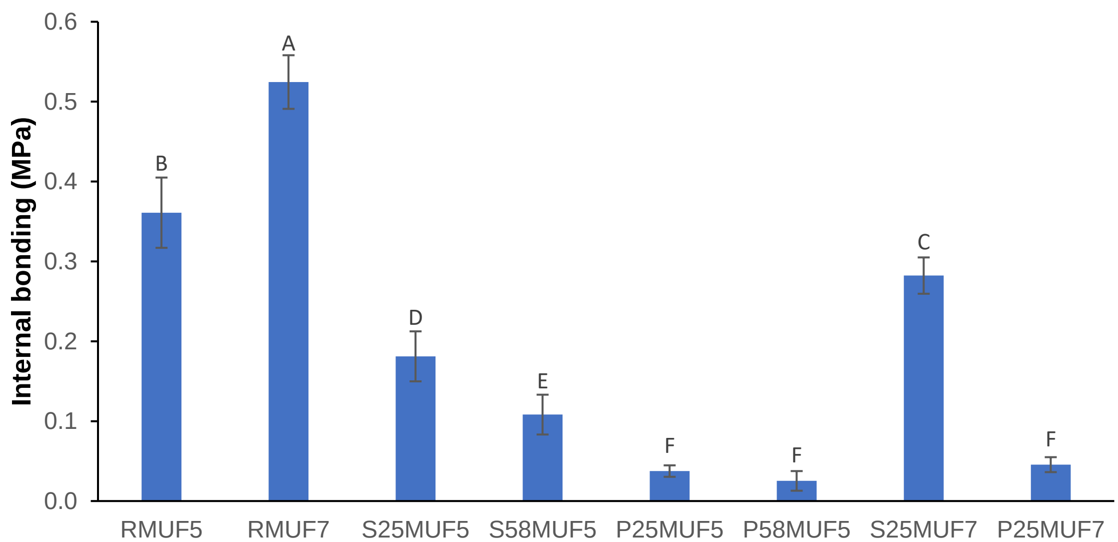

Fig. 16. Internal bond strength of MUF-bonded boards (letters above the error bars that are the same do not have a statistically significant difference by the Tukey´s test α = 0.05)

Effect of adhesive type (UF vs. MUF)

The adhesive type also significantly affected IB, with UF adhesive generally resulting in higher IB values than MUF adhesive, except for RUF7 (0.48 MPa) *vs.* RMUF7 (0.52 MPa), where the difference was not significant. The regression coefficient for adhesive type was +0.14 ($p < 0.01$). Differences in IB strength related to adhesive type ranged from 3% for reference samples to greater differences in pine particle samples with 7% resin application.

Effect of adhesive amount (5% vs. 7%)

The adhesive amount had a significant effect on IB, with 7% adhesive resulting in higher values, especially for reference and spruce bark samples. Tukey's test confirmed significant differences only for these samples. The regression coefficient for adhesive amount was +0.10 ($p < 0.05$). In conclusion, the highest IB values were achieved with a combination of spruce bark, smaller particles, MUF adhesive, and higher adhesive amount.

In this study, the IB strength values ranged from 0.06 MPa (P58UF5) to 0.29 MPa (S25UF7) and from 0.03 (P58MUF5) to 0.28 MPa (S25MUF7). These results were significantly lower compared to those reported by Pedieu *et al.* (2008), Papadopulos (2006), Yemele *et al.* (2008), Blanchet *et al.* (2000), and Medved *et al.* (2019), who achieved higher values (Table 3) due to the use of stabilizing adhesives, larger particle sizes, increased resin content, or a combination of bark and wood particles. The findings of this study were partially comparable to the data reported by Medved *et al.* (2020) and Muszynski and McNatt (1984), who demonstrated the influence of bark content and bark-to-wood ratios on panel cohesion.

Table 3. Overview of the Results of Physical and Mechanical Properties (TS, WA, MOR, MOE and IB)

Author	Sample	TS (%)	WA (%)	MOR (MPa)	MOE (MPa)	IB (MPa)
Blanchet (2000)	0% bark particles, 12% resin	14.1	-	8.3	1300	0.37
	50% bark particles, 14% resin	5.9	-	16.8	2800	0.60
Burrows (1960)	No overlay	4.3	5.4	6.5	1241	0.70
	Particle size from 2 to 9.5 mm	-	6.4	18.1	3068	0.57
	Particle size from 0.8 to 9.5 mm	-	7	18.7	3061	0.57
	Particle size from 2 to 4.75 mm	4.8	6.6	18.8	3144	0.62
Gupta *et al.* (2011)	Coarse particles	-	18.3	-	-	0.30
	Fine particles	5.1	6.3	9.8	1871	0.62
	Medium particles	18.4	31.8	4.7	990	0.26
	Mixed fractions	-	15.4	7.2	1684	0.97
Medved *et al.* (2019)	100% wood particles	11.6	98	-	-	0.55
	90/10 wood/bark particles	15.6	81.5	-	-	0.46
Medved *et al.* (2020)	100% wood particles	54	-	11.4	2480	0.21
	50/50 wood/bark particles	31	-	10.5	1790	0.29
Muszynski and McNatt (1984)	0% bark	9.6	48	19.6	3923	0.55
	100% bark	14.2	65	4.9	785	0.08
Papadopoulos (2006)	100% bark particles, 5% EMDI	9.1	-	11.9	-	0.51
	100% bark particles, 6% EMDI	7.8	-	12.3	-	0.55
Pedieu *et al.* (2008)	$P_{5\%}$ (birch bark, 5% PF)	3.2	-	-	-	1.41
	$P_{6.5\%}$ (birch bark, 6.5% PF)	-	-	-	-	1.45
	$P_{8\%}$ (birch bark, 8% PF)	8.3	-	-	-	1.14
Rishel *et al.* (1980)	Beech	-	-	4.1	1324	-
	Black cherry	-	-	6.7	2144	-
Yemele *et al.* (2008)	*BSB 2.6 to 5.0 mm	22.2	-	-	1327	0.13
	*BSB 5.0 to 7.0 mm	11.4	-	9.7	2376	0.38
	Control	8.2	-	26.5	3867	1.72
	*TAB 2.6 to 5.0 mm	11	-	5	1355	0.28
	*TAB 5.0 to 7.0 mm	10	-	-	2117	0.55
*(BSB) black spruce bark, *(TAB) trembling aspen bark						

CONCLUSIONS

1. Spruce bark consistently outperformed pine bark across most tested parameters. Board samples made from spruce bark particles exhibited higher internal bond (IB) and modulus of rupture (MOR), with statistically significant differences observed in several comparisons. Furthermore, spruce bark boards demonstrated superior resistance to water absorption (WA) and *thickness swelling* (TS), particularly when bonded with urea-formaldehyde (UF) adhesive. Based on these findings, spruce bark is recommended as the preferred bark for further investigation and potential integration into particleboards manufacturing.
2. Particle size had a significant impact on the performance of the samples. Larger particles (5 to 8 mm) generally resulted in higher modulus of elasticity (MOE) and resistance to WA compared to smaller particles (2 to 5 mm). However, smaller particle sizes improved IB strength and TS resistance. This dual behavior suggests that a mixture of particle sizes could be considered in future research, with a focus on optimizing the balance between mechanical and physical properties.
3. UF adhesive demonstrated superior overall performance compared to MUF adhesive, particularly in terms of TS, WA, and IB strength. This superior performance of UF adhesive was consistent across most bark wood species and particle sizes. While MUF adhesive yielded competitive results in MOR and MOE, the differences were generally not statistically significant. Therefore, UF adhesive is recommended for blending bark fractions with industrial wood particles.
4. An increase in adhesive content from 5% to 7% resulted in significant improvements in several properties, including IB strength, MOR, and WA. This trend was particularly pronounced in reference samples and in samples made from spruce bark particles. Although higher adhesive content increases production costs, the improved performance justifies the use of 7% adhesive application for both research and manufacturing purposes.
5. Based on the findings, future research will focus on blending spruce bark particles with industrial wood particles bonded with UF adhesive to identify the optimal blend for achieving industrial-grade quality.

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