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Properties of Phenol-Formaldehyde Resin Modified with Kraft Lignin for Particleboard Production

Svojstva fenol-formaldehidne smole modificirane kraft ligninom za proizvodnju ploča iverica

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ABSTRACT • *Lignin is a natural polymer with a phenolic structure, which makes it suitable as a substitute in phenol-formaldehyde (PF) resins. In this study, unmodified kraft lignin was used as a substitute in a commercial phenol-formaldehyde resin, with the substitution rate being 10 %. This resin was further used to produce a single-layer particleboard using hot pressing in a laboratory press. Results of physical and mechanical tests showed that the addition of lignin to the PF resin negatively affected these properties, while particleboards bonded with lignin-modified PF resin met the requirements of the standard for lower-class particleboards. Scanning electron microscopy confirmed cohesive failures in ruptured particleboards bonded with both the reference resin and the lignin-modified PF resin. For the lignin-modified PF resin, particles of undissolved lignin were found in the resin. Further testing showed no difference in the emission of volatile organic compounds between the variants.*

KEYWORDS: *Wood-based composite; lignin; adhesive; mechanical properties; physical properties*

SAŽETAK • *Lignin je prirodni polimer fenolne strukture, što ga čini prikladnom zamjenom za fenol-formaldehidne (PF) smole. U ovom je istraživanju nemodificirani kraft lignin upotrijebljen kao zamjena za komercijalnu fenol-formaldehidnu smolu, a stopa supstitucije bila je 10 %. Takva je smola dalje rabljena za proizvodnju jednoslojne iverice vrućim prešanjem u laboratorijskoj preši. Rezultati ispitivanja fizičkih i mehaničkih svojstava tako proizvedenih ploča pokazali su da dodatak lignina PF smoli negativno utječe na svojstva ploča, ali ipak ploče iverice s PF smolom modificiranom ligninom udovoljavaju standardima za iverice niže klase. Pretražna elektronska mikroskopija potvrdila je kohezivne lomove u polomljenim ivericama s referentnom smolom i PF smolom modificiranom*

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ligninom. U PF smoli modificiranoj ligninom pronađene su čestice neotopljenog lignina. Daljnjim ispitivanjima među istraživanim varijantama ploča iverica nije uočena razlika u emisiji hlapljivih organskih spojeva.

KLJUČNE RIJEČI: *kompozit na bazi drva; lignin; ljepilo; mehanička svojstva; fizička svojstva*

1 INTRODUCTION
1. UVOD

Particleboard (PB) is a composite material consisting of wood particles that are bonded together using synthetic adhesives, primarily urea-formaldehyde (UF), phenol-formaldehyde (PF), melamine-formaldehyde (MF), and isocyanate (Jiang *et al*., 2023). The European production of PB mainly used for furniture, interior elements and cladding was approximately 44 million m^3 in 2022 (42 % of global production) (Scharf *et al*., 2023). Wood particles of lower quality wood, wood residues (sawdust and shavings), recycled wood or non-wood alternative materials can be used for PB production (Auriga *et al*., 2024; Niemz and Sandberg, 2022). It is the use of recycled materials and the possibility to recycle the PB itself that is their essence in the circular economy (Petrova *et al*., 2023). The possibility of using lignin in binders for PB production would further enhance the environmental aspect of this product.

PF are synthetic resins produced by reacting phenol with formaldehyde (Kumar and Pizzi, 2019). The term synthetic resin means that the substances for their synthesis are products of the petrochemical industry (Zhao *et al*., 2011).

For wood and paper-based materials, PF resins are currently one of the most widely used resins for their production (Thébault *et al*., 2017). The reason for their considerable use is the relatively low cost associated with their resistance to moisture, weathering and high temperatures (Pizzi, 2014). Specifically, they are predominantly utilized in the production of wood-based composites that must be resistant to environmental factors (Pilato, 2010).

The use of formaldehyde-based resins results in the release of formaldehyde into the environment, which is a significant concern due to its carcinogenic effects (IARC, 2023). At the same time, phenol is also classified as a highly toxic substance and its exposure limits are carefully controlled (Gardziella *et al*., 2000).

Lignin is a complex polymeric substance located within the cell walls of vascular plants. It represents the second most abundant organic polymer in nature, following cellulose (Abhilash and Thomas, 2017; Nadányi *et al*., 2022). Its main function is to strengthen secondary cell walls and promote water transport in plants (Whetten and Sederoff, 1995). Its extraction is often linked to industrial processes such as pulp production in the paper industry. The by-product of this process, black liquor, is a source of lignin for further use (Bajpai, 2018).

In terms of utilization, lignin has traditionally been used for combustion in recovery boilers to provide additional energy (Dessbesell *et al*., 2020). However, modern technologies allow lignin to be used in various sectors. For example, it can be used in the production of polymers (resins or plastics), carbon fibers, as a binder in pelletizing, and it also finds applications in the pharmaceutical and cosmetic industries. Last but not least, other valuable chemical products can be obtained from lignin (Calvo-Flores *et al*., 2015).

The adhesive properties of lignin and its potential use in adhesives have been studied for over 100 years, but only a few industrial applications have been developed in that time. The appeal of lignin as a substitute in wood adhesives is attributed to its natural origin, phenolic characteristics, high availability, and low cost (Karthäuser *et al*., 2021; Saražin *et al*., 2022).

The biggest difficulty in the application of lignin in adhesive systems is its low reactivity. This leads to slow curing of adhesives, which is crucial in the production of composite materials. Untreated lignin is economically disadvantageous for applications that require fast curing. However, the reactivity of lignin can be enhanced through various modifications, such as phenolation, methylation, and demethylation, which improve its reactivity with formaldehyde (Hemmilä *et al*., 2013; Zhang *et al*., 2013).

It was the high phenolic content of lignin that led to the idea of the possibility of replacing phenolics with lignin in the production of PF resins (Solt *et al.*, 2019), where the resulting lignin-phenol-formaldehyde (LPF) resins were tested for use in the production of MDF, DTD or OSB to evaluate their potential applications (Jiang *et al*., 2021).

Based on many studies, it has been shown that the strength of the bonded joint inside wood-based composite materials decreases with increasing the content of unmodified lignin (Ghorbani *et al*., 2016; Moubarik *et al*., 2013; Pinheiro *et al*., 2017; Yang *et al*., 2015). This is the reason for the lower reactivity of lignin and, therefore, up to 30 – 50 % of phenol can be replaced by unmodified lignin in PF resins without significant changes in the resin properties (Xu and Ferdosian, 2017). The molecular weight of lignin, which affects the final viscosity of the synthesized resin, is an essential property for some applications *(Huang et al*., 2022).

The price of lignin depends on its quality and purity, with lower quality lignin priced at less than USD

300/t, while high quality lignin can exceed USD 750/t (Mason, 2021). Lignin modification increases the reactivity of lignin, but the feedstock and energy costs lead to an increase in the price of the modified lignin *(Liu et al., 2024; Nadányi et al., 2022; Paananen et al.*, 2021) and these are challenging technological steps.

The primary objective of this study is to examine the effects of incorporating kraft lignin as an additive in phenol-formaldehyde (PF) resins on the properties of particleboards (PBs) produced using these modified resins. By applying the developed resins in PB manufacturing, the study aims to yield critical insights into the interactions between the resin and wood during the board formation process, as well as their influence on the mechanical and physical properties of the resulting particleboards. The results of the properties will then be compared with the requirements of ČSN EN 310 (1995) in order to compare the individual parameters with each other against this standard and subsequently classify them into a quality category.

The broader aim of this research is to develop a kraft lignin-modified PF resin with the potential for large-scale industrial production.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

2.1 Materials
2.1. Materijali

Softwood particles supplied by DDL Lukavec company (Dřevozpracující družstvo Lukavec, Czech Republic) were used to produce the middle layer of particleboards with a moisture content of 8 %. The phenol-formaldehyde resin Lignofen G/3/D (LERG SA, Poland) was used. This is a resol-type resin of dark red color that cures at a temperature of 130 °C, with a curing time of 80 to 120 seconds.

Kraft lignin used in the preparation of lignin-phenol-formaldehyde resin was obtained by precipitation from hardwood black liquor by Mondi company (Mondi SCP, a.s., Slovakia). Isolation was carried out by adding sulfuric acid to the black liquor until pH 2-3 was reached and lignin was precipitated. Subsequently, the lignin was filtered and washed three times with distilled water to achieve pH 5-6. After reaching the desired pH, the lignin was dried at 60 °C and then ground to the desired fraction using a knife mill IKA MF 10 basic (IKA, Germany).

2.2 Production of lignin-phenol-formaldehyde resins
2.2. Proizvodnja lignin-fenol-formaldehidnih smola

Phenol-formaldehyde resins with 0 % (reference) and 10 % lignin content (relative to the dry matter of the adhesive and lignin) were prepared. The desired amount of lignin was added to the phenol-formaldehyde resin. The lignin was first mixed using an anchor stirrer and then, for greater homogeneity of the adhesive mixture, a disperser Yellow line DI 25 basic (IKA, Germany) was used, and the mixture was stirred for 5 minutes.

2.3 Particleboard production
2.3. Proizvodnja iverice

For testing the properties of particleboards bonded with PF resin with 0 % and 10 % lignin content, single-layer PBs 12 mm thick with a target density of 650 kg/m^3 were manufactured. To maintain the correct resin-to-wood ratio, the moisture content of the particles was first measured using a moisture analyzer MB-23 (Ohaus, USA). Then, the desired amount of particles was weighed and placed into a rotary drum blender. The resin content in PB was chosen to be 10 % in dry matter of the resin. The adhesive mixture was heated to 60 °C to reduce viscosity and applied by spraying under pressure in the spreader to ensure even distribution onto the particles.

Subsequently, the adhesive-coated particles were layered into a mold, after which the particle mat was subjected to compression using a hydraulic press. The samples were pressed under a pressure of 3.5 MPa at a temperature of 140 °C for a duration of 4 minutes. Following the pressing process, the boards were removed and conditioned at 20 °C and 65 % relative humidity for a period of 96 hours.

2.4 Methodology of particleboards testing
2.4. Metodologija ispitivanja iverice

2.4.1 Vertical density profile
2.4.1. Gustoća iverica po debljini

Vertical density profile (VDP) analysis was performed employing a DPX300-LTE X-ray density analyzer (IMAL PAL GROUP, Italy). Four samples, each measuring 50 mm × 50 mm × 12 mm, were subjected to measurement for every variant. The VDP values were then averaged within each variant to construct density curves, enabling subsequent comparison among the individual variants VDP curves.

2.4.2 Moisture uptake and thickness swelling
2.4.2. Upijanje vode i debljinsko bubrenje

To evaluate moisture resistance, 20 samples with dimensions of 50 mm × 50 mm were prepared for each variant. The samples were first dried in an oven at 103 °C until a constant weight was achieved, ensuring a moisture content of 0 %. Initial thickness (t_0) and weight (m_0) measurements were recorded for the dried samples.

Following this, the samples were immersed in water at 20 °C for 24 hours. After immersion, the samples were placed on a mat for 10 minutes to allow surface water to drain. Subsequently, measurements of thickness (t_w) and weight (m_w) were taken for each sample.

From these measurements, thickness swelling (TS) and moisture uptake (MU) were calculated as percentages using the following equations (ČSN EN 317, 1995):

$$TS\ (\%) = \frac{t_w - t_0}{t_0} \cdot 100 \tag{1}$$

Where t_w represents the board thickness after 24 hours of water immersion, and t_0 denotes the board thickness after drying to 0 % moisture content.

$$MU\ (\%) = \frac{m_w - m_0}{m_0} \cdot 100 \tag{2}$$

Where m_w represents the board weight after 24 hours of water immersion, and m_0 denotes the board weight after drying to 0 % moisture content.

2.4.3 Bending strength
2.4.3. Čvrstoća na savijanje

Bending strength (*MOR*) and modulus of elasticity in bending (*MOE*) were evaluated in accordance with the (ČSN EN 310, 1995) standard, utilizing the three-point bending test method on a TT 2850 universal testing machine (TIRA, Germany). For each variant, ten particleboard samples with dimensions of 290 mm × 50 mm × 12 mm were prepared. The support span (*l*) was set at 240 mm. *MOR* and *MOE* values were subsequently calculated using the standard equations prescribed in the testing protocol:

$$MOR\ (MPa) = \frac{3 \cdot F_{\max} \cdot l}{2 \cdot b \cdot t^2} \tag{3}$$

Where $F_{\max}$ represents the maximum force applied to the sample, measured in newtons (N), l denotes the distance between supports (240 mm), b is the width, and t is the thickness of the sample, both measured in millimeters (mm).

$$MOE\ (MPa) = \frac{l^3 \cdot (F_2 - F_1)}{4 \cdot b \cdot t^3 \cdot (a_2 - a_1)} \tag{4}$$

Where l represents the support span of 240 mm, F_1 corresponds to 10 % and F_2 to 40 % of the maximum load ($F_{\max}$) in newtons (N), and b and t represent the width and thickness of the sample, respectively, in millimeters (mm). Let a_1 and a_2 denote the deflection increments at the center of the test specimen, measured in millimeters (mm), corresponding to the load difference between F_1 and F_2.

2.4.4 Internal bonding
2.4.4. Čvrstoća na raslojavanje

The determination of internal bonding (*IB*) was conducted in accordance with the procedures specified in ČSN EN 319, 1994. For each variant, ten samples with dimensions of 50 mm × 50 mm × 12 mm were prepared. The exact surface dimensions of each sample were measured prior to testing. The samples were then bonded to beech wood boards using Bison Power adhesive, a two-component polyurethane glue, in preparation for *IB* testing.

After bonding, the samples were allowed to cure under constant pressure for 24 hours. The *IB* test was performed using a TT 2850 universal testing machine (TIRA, Germany). IB values were calculated using the specified equation:

$$IB\ (MPa) = \frac{F_{\max}}{a \cdot b} \tag{5}$$

Where $F_{\max}$ denotes the maximum force applied to the sample, measured in newtons (N), while a represents the length and b signifies the width of the sample, both measured in millimeters (mm).

2.4.5 Microscopic analysis
2.4.5. Mikroskopska analiza

The PB samples were subjected to Scanning Electron Microscopy (SEM) analysis using a MIRA 3 electron microscope (Tescan Orsay Holding, Czech Republic) equipped with a secondary electron detector and operated at 15 kV acceleration voltage (Hýsek and Żółtowska, 2022). After the internal bonding test, breached samples were selected for SEM examination. Prior to microscopic sample preparation, the samples were coated with a thin layer of gold using a sputtering technique.

2.4.6 Volatiles emission analysis
2.4.6. Analiza emisije hlapljivih spojeva

Differences among the samples were investigated using solid-phase microextraction (SPME) coupled with two-dimensional comprehensive gas chromatography and time-of-flight mass spectrometry (GC×GC-TOF-MS).

The gas chromatograph used was an Agilent Technologies 7890B (USA), equipped with an HP-5MS UI capillary column (30 m, 0.25 mm inner diameter, 0.25 µm film thickness, Agilent USA). This was coupled via a consumable-free modulator to a second-dimensional column, VF-17 (1.5 m, 0.1 mm inner diameter, 0.1 µm film thickness, Agilent USA). Helium was employed as the carrier gas at a flow rate of 1 ml/min. A splitless injection was performed using a hot split/splitless injector set at 275 °C. After a 2-minute solvent delay, the oven temperature was raised from an initial 40 °C at a rate of 5 °C/min to 120 °C, followed by an increase of 20 °C/min to 300 °C. The second-dimensional GC oven and modulator adhered to this temperature program with offsets of 5 °C and 15 °C, respectively. The modulation period was set to 5 seconds, with a hold time of 2 minutes, resulting in a total GC run time of 29 minutes. The separated compounds were ionized in the ion source of the TOF mass spectrometer

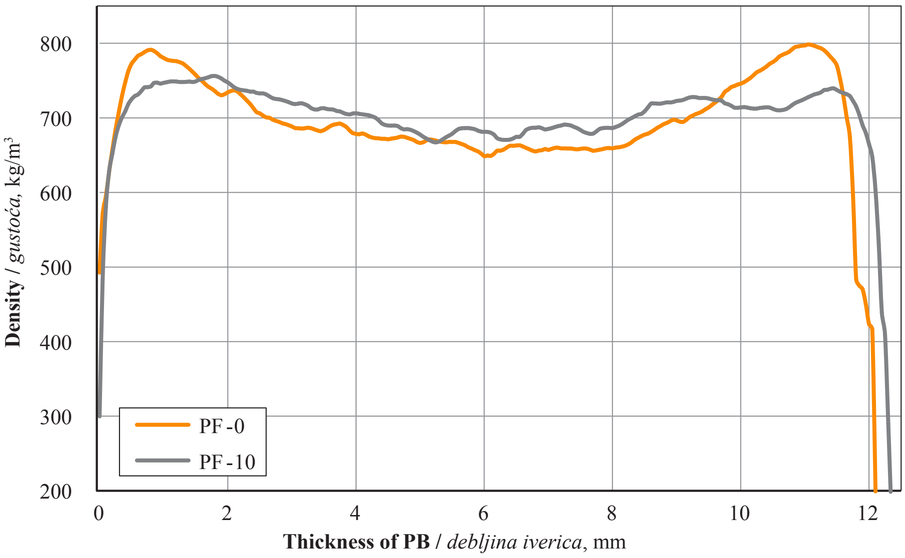

Figure 1 Vertical density profile of particleboards
Slika 1. Gustoća iverica po debljini

at 70 eV in electron impact mode, with full spectral information (35–500 Da) recorded at a rate of 100 times per second.

For tentative identification of the compounds, spectral similarity was assessed by comparing the measured and deconvoluted spectra with mass spectra in the National Institute of Standards and Technology mass spectral library (NIST, 2017).

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

3.1 Vertical density profile
3.1. Gustoća iverica po debljini

The vertical density profile (VDP) graph (Figure 1) illustrates that both variants exhibit highly comparable VDP curves, characterized by increased density at the surfaces and reduced density in the central region of the particleboard (PB). This phenomenon can be attributed to the compression of the PB. Notably, the PF-0 samples demonstrate higher density in the surface layers compared to the PF-10 samples, which exhibit a relatively flat VDP profile. The reason for the more flat VDP is probably due to the higher viscosity of the lignin-containing resin, which resulted in a less uniform distribution of the adhesive on the individual wood particles. However, the results indicate that the lignin content in the resin did not significantly influence the density distribution across the cross-section of the board.

3.2 Moisture uptake and thickness swelling
3.2. Upijanje vode i debljinsko bubrenje

The results of MU (Figure 2A) and TS (Figure 2B) show that the addition of lignin had a negative effect on the moisture interaction with the particleboards compared to the reference PF resin, which reaches the values required by (ČSN EN 302-1, 2013) for class P3. Although kraft lignin is inherently hydrophobic, it can be posited that the negative moisture interaction observed in PF bonded particleboards containing lignin is

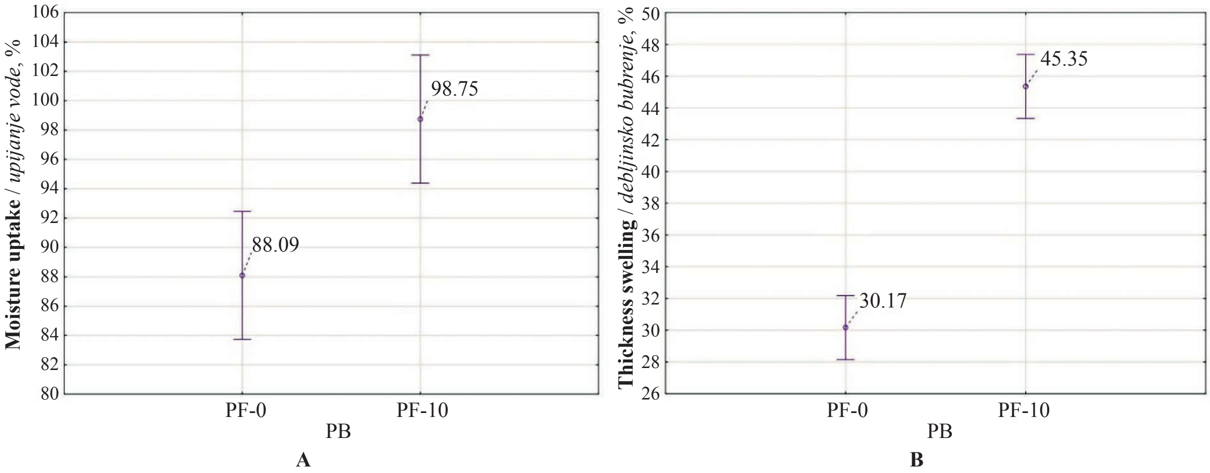

Figure 2 Moisture uptake (A) and thickness swelling (B) of particleboards
Slika 2. Upijanje vode (A) i debljinsko bubrenje (B) iverica

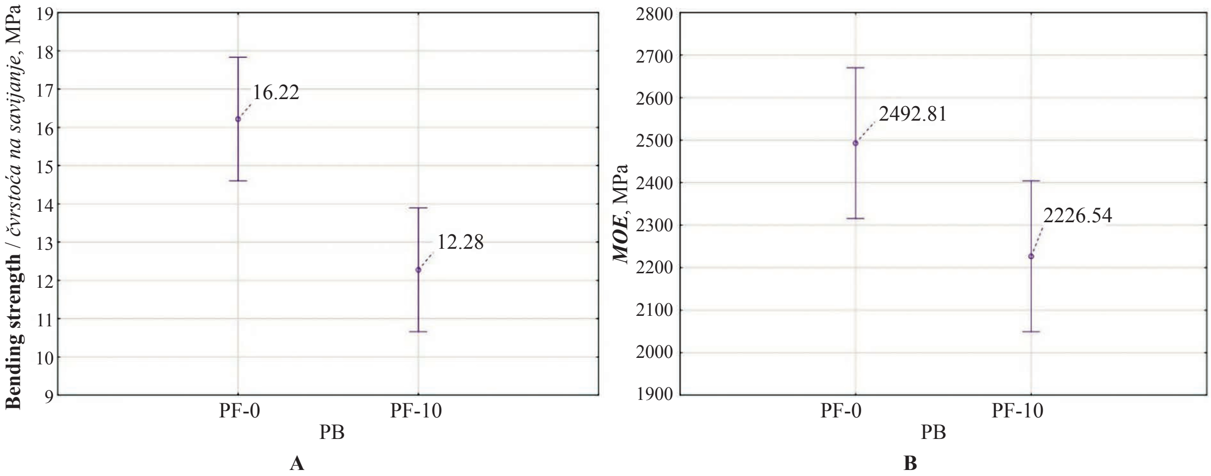

Figure 3 Bending strength (A) and modulus of elasticity (B) of particleboards
Slika 3. Čvrstoća na savijanje (A) i modul elastičnosti (B) iverica

attributable to the presence of lignin in the resin. This may lead to imperfect bonding sites between the wood particles and the resin, facilitating enhanced moisture penetration into the particleboard structure. Electron microscope images of the glued joint confirm our hypothesis (see chapter *3.5 Microscopic analysis*).

Similar results, where increasing substitution of unmodified lignin in PF resins leads to increased moisture uptake, were obtained in a study by (Younesi-Kordkheili, 2022). Here, the results are attributed to the degradation of free lignin particles by water absorption, since these particles, due to their nature, do not contribute to crosslinking with phenol and formaldehyde.

(Pizzi, 2014) further reports that, upon curing, PF resin forms methylene bridges, which are resistant to hydrolysis. In contrast, PF resins with added lignin form different bonds (e.g., C-O) that are more sensitive to moisture.

3.3 Bending properties
3.3. Svojstva savijanja

The incorporation of lignin also adversely affected the mechanical properties of the tested particleboards. With 10 % lignin replacement in PF resin, a significant decrease in PB properties can be seen compared to the use of commercial resin. The boards bonded with commercial resin reached the requirements for P4 class of PB according to (ČSN EN 302-1, 2013) (15 MPa and 2300 MPa) in *MOR* (Figure 3A) and *MOE* (Figure 3B) results (16.22 MPa and 2492.81 MPa). The boards bonded with PF-10 resin from the *MOR* and *MOE* point of view (12.28 MPa and 2226.54 MP) meet the requirements for PB category P2 for furniture purposes according to (ČSN EN 302-1, 2013) (11 MPa and 1800 MPa).

The findings of the study conducted by (Younesi-Kordkheili, 2022) indicate that the *MOR* and *MOE* of particleboard test samples decline as the proportion of kraft lignin in PF resins increases. This reduction is attributed to the lower reactivity of kraft lignin, resulting in a diminished formation of hydroxyl bonds. This reduces the crosslinking between lignin and resin components, causing a decrease in the cohesive strength of cured resin within PB.

The lower results of *MOR* and *MOE* of the PF-10 variant were expected due to the lower density in the surface layers of the PF-10 variant seen in the VDP results.

3.4 Internal bonding
3.4. Čvrstoća na raslojavanje

The *IB* results again show a decrease in mechanical properties for PB bonded with resin with the addition of lignin. However, despite the drop from 0.9 MPa for PF-0 samples to 0.57 MPa for PF-10 bonded boards, these boards met the requirements of (ČSN EN 302-1, 2013) for class P5 (0.45 MPa), and the results are only slightly below the 0.6 MPa required for class P6 boards.

In the tested samples, black colored areas could be observed inside the PB structure bonded with PF-10

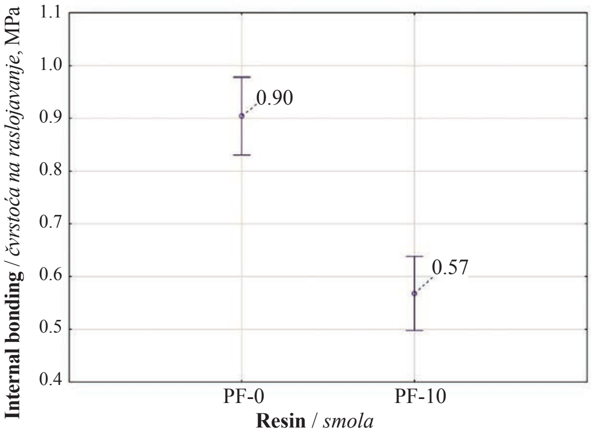

Figure 4 Internal bonding of particleboards
Slika 4. Čvrstoća iverica na raslojavanje

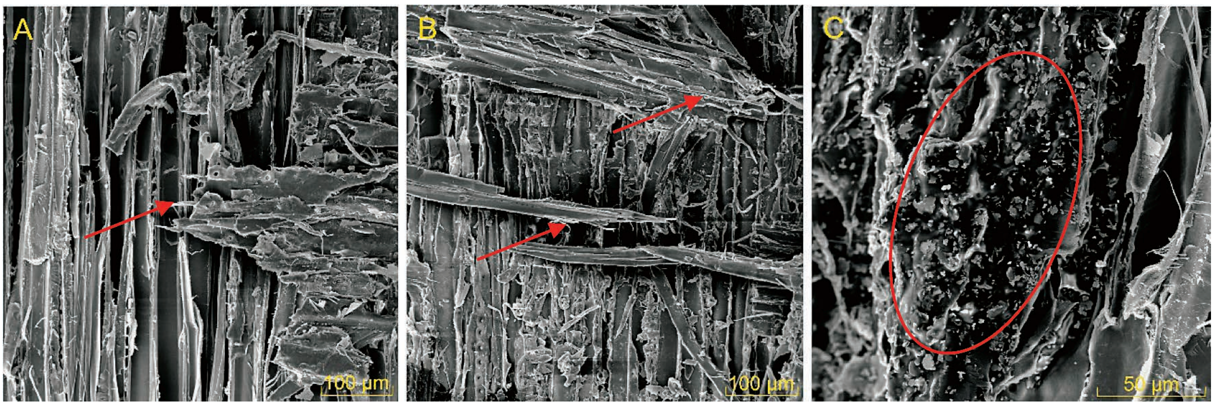

Figure 5 SEM images of ruptured samples of (A) PF-0 variant, (B) PF-10 variant showing cohesive failure of wood (red arrows) and (C) PF-10 variant showing lignin cumulation (red ellipse)
Slika 5. SEM slike polomljenih uzoraka: A varijanta PF-0, i B varijanta PF-10 pokazuju kohezijski lom po drvu (crvene strelice), a C varijanta PF-10 pokazuje nakupljanje lignina (crvena elipsa)

resin after the test. These spots identified clusters of lignin particles that were poorly mixed in the resin and could have caused poor bonding between the wood particles and the resin during manufacturing, which would have resulted in a deterioration of the mechanical properties of these PBs.

In their study, Donmez Cavdar *et al.* (2008) report that IB is very sensitive to the distribution of resin on the particles and to the VDP of individual panels. Here we assume that the decrease in IB for the PF-10 variant is partly due to the slightly lower density of the PB core layer.

Unmodified kraft lignin is less reactive and needs longer pressing time (Hu *et al*., 2011). In a previous study by (Němec *et al*., 2023), focusing on the production of lignin-PF resins for paper-based laminates, the effect of incomplete dissolution of lignin particles in the prepared resin was also observed, even with higher temperatures and longer pressing times. At the same time, extending the pressing time would significantly increase the economics of commercial scale PB production. This resulted in an increase in the molecular weight of the adhesive and therefore a deterioration in adhesion. Indeed, undissolved lignin molecules can behave as impurities forming a weak bond between the substrate, leading to a reduction in mechanical properties.

3.5 Microscopic analysis
3.5. Mikroskopska analiza

Figure 5a-b depicts the character of bond rupture in the ruptured boards. In both cases, cohesive failure of wood was observed, identifying the high performance of the adhesive variants used. In contrast to urea-formaldehyde resin modified with lignin, adhesive failures between wood and adhesive were not observed (Němec *et al*., 2024). However, thanks to the manual manufacturing of adhesive as well as the whole composite, insufficient dispersed lignin in the PF resin was found (Figure 5c). This failure of desperation could contribute to the lower mechanical properties of the composites in comparison with the reference.

3.6 Volatiles emission analysis
3.6. Analiza emisije hlapljivih spojeva

Typical compounds for wood-based materials e.g. terpenes, aldehydes and short chain fatty acids were detected in both board samples. Comparing the intensity of each selected compound in gas-chromatographic record of both samples, it was proved that both emitted the same profile of compounds. Within uncertainty of measurement, the intensity of responses, showing concentrations of compounds, was the same with exception of acetic acid. Modification of adhesive formula by addition of lignin leaded to significant (by 55 % lower) decrease in emission of this compound. While acetic acid is known to be evaporating from wood fibreboard containing phenolic glue (Roffael, 2017), it can be also used as a reactant in acetylation of kraft lignin (de Oliveira *et al*., 2020). In this reaction, the hydroxyl groups in lignin react with acetic acid, leading to the formation of acetylated lignin and water as a by-product. We assume that the emission decrease is due to the reaction of the present acetic acid with added lignin.

4 CONCLUSIONS
4. ZAKLJUČAK

Replacing part of the PF resin with lignin caused a decrease in moisture resistance and a decrease in mechanical properties. The results of *MOR* and *MOE* showed a decrease from 16.2 and 2492 MPa (PF-0) to 12.3 and 2227 MPa (PF-10), which still meets the requirements of the P2 board standard. For IB, there was a decrease in strength from 0.9 MPa (PF-0) to 0.57 MPa (PF-10), and this variant does not closely meet the requirements of the Type P6 standard (0.6 MPa). Scanning

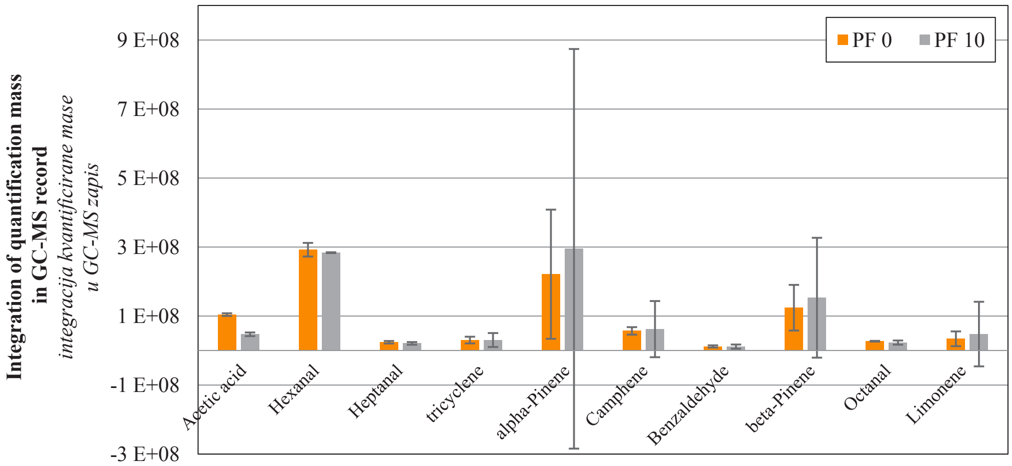

Figure 6 Comparison of selected volatile compounds mean emission in samples of board glued by standard phenolic (PF) and lignin modified glue (PF 10). Error bars represent expanded uncertainty of determination (*U*=2·*SD*) covering 95 % confidence interval.
Slika 6. Usporedba odabranih emisija hlapljivih spojeva u uzorcima ploča lijepljenih standardnim fenolnim ljepilom (PF) i ligninom modificiranim ljepilom (PF 10). Trake pogrešaka označavaju proširenu nesigurnost (*U*=2·*SD*) za interval pouzdanosti od 95 %.

electron microscopy showed cohesive failure in the wood for both tested variants. At the same time, the images showed the occurrence of small undissolved kraft lignin particles in the prepared resin. The tested modification of wood particleboard did not influence the emission of volatile organic compounds from material with exception of acetic acid, which decreased to one half of the original value. The presented method of PF resin modification is relatively simple and can be readily implemented in industry. By incorporating lignin content at 10 %, this method allows the production of particleboards that meet industry standards. Furthermore, it is believed that by selecting the appropriate technology, the standardized properties of these particleboards can be further enhanced. For future research, it is recommended to focus on solving the problem of increasing viscosity when lignin is added to the adhesive mixture, which negatively affects the subsequent uniform application of the resin to the wood particles during manufacturing. An interesting step would also be to test the behavior of a different type of lignin in the tested resin or, despite this being a technologically demanding and costly process, to test the effects of kraft lignin modification on the properties of particleboards compared to the variant tested in the present study.

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