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Application of soy starch as a binder in HDF technology

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Abstract: *Application of soy starch as a binder in HDF technology.* The aim of the research was to determine the selected properties of a dry-formed high-density fibreboard (HDF) bonded with soya flour as an environmentally friendly binding agent. The scope of work included the production of boards under laboratory conditions with different mass percentages of soy flour, i.e. 10%, 12%, 15% and 20%. Different mechanical and physical properties were determined, namely modulus of rupture, modulus of elasticity, the screw withdrawal resistance of the panels, internal bonding strength, density profile, thickness swelling, water absorption and surface water absorption. The results showed that increasing the proportion of soybean binder by weight contributes to improving mechanical properties but worsens physical properties.

Keywords: fibreboard, HDF, soy, binder, physical properties, mechanical properties

INTRODUCTION

Wood-based materials are produced by bonding wood fibers, carpentry boards, or veneers using adhesive. Currently, synthetic resins are mainly used in the production of wood-based materials: phenol-formaldehyde (PF), urea-formaldehyde (UF), and melamine-formaldehyde (MF) (Kumar and Legate, 2022). Synthetic adhesives have excellent bonding properties, sufficient flexibility, relatively low cost, suitable resistance to water and various chemicals, as well as high thermal stability. Despite their numerous advantages, synthetic adhesives are not environmentally friendly as they emit significant amounts of formaldehyde, which is considered a highly toxic substance, posing a threat to the environment and human health. The release of formaldehyde has a serious impact on human health, causing skin allergies, respiratory irritation, nausea, leukaemia, and nasopharyngeal cancer (Kristak et al., 2022). In recent times, there has been an increased interest in the development of natural-origin adhesives due to restrictions on formaldehyde emissions and the demand for more environmentally friendly products (Kumar and Leggate, 2022).

Wood adhesives based on starch have gained significant industrial and research interest due to their wide availability, low cost, and renewability. However, starch adhesives have several limitations that restrict their use in the production of wood composites, such as poor water resistance, low bonding strength, and low initial viscosity (Kumar and Leggate, 2022). Zheng et al. (2017) investigated the influence of thermal pretreatment of starch at 70, 80, and 90°C on the copolymerization reaction with vinyl acetate (VAc) and the performance of starch adhesive. The research showed that higher temperatures led to improved results for starch-based adhesives. Hikmah et al. (2021) produced and tasted a starch-based adhesive using cassava peel and citric acid. The particleboard bonded with the natural adhesive exhibited positive effects on its physical properties.

Soy proteins are relatively inexpensive, easy to process, do not require high pressing temperatures, and can be used under high wood moisture conditions. However, soy adhesives are characterized by low strength and poor water resistance compared to industrial adhesives. Low water resistance can be overcome through enzymatic modifications, cross-linking, or chemical denaturation (Kumar and Leggate, 2022). Jang and Li (2015) produced a five-layer plywood bonded with a natural adhesive made from soy flour (SF) and magnesium oxide (MgO). The authors demonstrated that the produced plywood meets the requirements for water resistance of interior panels. Li et al. (2009) prepared medium-density fiberboard (MDF) using a soy protein-based binder modified with sodium dodecyl sulfate (SDS). The research showed that the MDF board produced using the modified soy protein adhesive exhibits properties similar to traditional boards.

Tannin-based adhesives are used in the production of particleboard and plywood. Tannins can be categorized into hydrolysable tannins or condensed polyflavonoid tannins, which are used in research on wood adhesives (Kumar and Leggate, 2022). Tannin resins aid in curing, reduce costs, and exhibit good water resistance. However, unmodified tannin adhesives are not suitable for exterior applications, so they are often subjected to modifications to improve their physical and mechanical properties, as well as their resistance to weathering factors (Hussin et al., 2022).

Wood adhesives based on plant oils are an interesting alternative to commercial resins. Plant oils are relatively inexpensive, renewable, and widely available. Addis et al. (2020) prepared an adhesive based on linseed oil and investigated its strength. The authors examined the influence of curing agent selection, wood species, pressing time, and spreading time on the adhesive properties. The research showed that the adhesive based on linseed oil is a suitable binder for the tested wood species and exhibits good shear strength.

Citric acid is known for its good wood bonding capability, making it suitable as a natural binder in the production of wood-based materials. Umemura et al. (2013) created a particleboard bonded with citric acid and sucrose. The research showed that with an increasing ratio of sucrose to citric acid, the mechanical properties improve and water resistance increases.

Latex, a biopolymer derived from the rubber tree, is characterized by low-temperature flexibility and high tensile strength. Particleboards produced with natural latex exhibit good properties for use as thermal insulation materials. Increased latex content in the boards does not affect density but improves water resistance (Nakanishi et al., 2018).

The aim of this research was to evaluate the selected mechanical and physical properties of high-density fiberboards produced with different amounts of soy flour as a binder.

MATERIALS AND METHODS

Materials

The research material consisted of dry-formed fiberboard created under laboratory conditions. The binder used in the study was soy flour from ZPGU ROMA (Czerwińska 3a Street, 09-450 Wyszogród, Poland) with 48% protein, 1.2% fat and 6% moisture content. The wood fibers with a moisture content of about 4% used in the production of fiberboards were industrially harvested and consisted of 95% pine wood (*Pinus sylvestris* L.). An industrial melamine-urea-formaldehyde resin (MUF) with 9% melamine by weight and 65% dry matter, 2% hardener by weight NH_4NO_3 was used to produce the reference panels. The curing time of the adhesive mass at 100°C was 89 s. No hydrophobic agent was used to produce the boards.

When mixing wood fibers with soybean flour, a spray of distilled water was used at 77% with respect to the dry weight of the binder.

Production of the panels

A nominally 3 mm-thick fibreboard, with a nominal density of 900 kg/m^3 and resination by soy flour of 10%, 12%, 15% and 20% by weight (hereinafter called variant 10, 12, 15, and 20). The resination of reference panels, bonded with the use of industrial, MUF binder (hereafter referred to as the reference variant) was 12%. Wood fibers were placed in a drum mixer. While the fibers were being mixed, soy flour was gradually added, and distilled water was sprayed with an air gun. The pressing parameters were the following: temperature 200 ºC, maximum unit pressure 2.5 MPa and pressing time factor 18 s/mm of nominal panel thickness. Before testing, all samples were conditioned in atmospheric air pressure at 20°C and 65% relative humidity to achieve constant weight.

Characterization of the panels

The produced HDF boards were tested to determine their mechanical and physical properties. The following mechanical properties were tested: modulus of rupture (MOR) and modulus of elasticity (MOE) at bending according to EN 310:1994, screw withdrawal resistance (SWR) according to EN 320:2011, tensile strength perpendicular to the plane of the board (internal bond, IB) according to EN 319:1999. A number of 8 samples from each board variant were used for testing, except for the modulus of rupture and modulus of elasticity at bending, where 16 samples from each board variant were tested. The following physical properties of the manufactured panels were investigated: density profile using a device (Laboratory Density Profile Measuring System) from Grecon (3 samples from each type of panels were selected for testing; the most representative profile was then shown in the graph), swelling in thickness (TS), water absorption (WA) after water immersion based on EN 317: 1999, (no less than 8 samples from each variant were used) and surface absorption (SWA) based on EN 382- 2:2001 (the test was performed on 2 samples from each variant). The results were examined using analysis of variance (ANOVA) and Student's t-test (α= 0.05) was performed to determine the statistical significance of differences between factors. The results shown in the graphs represent mean values and standard deviation.

RESULTS AND DISCUSSION

Modulus of rupture

Figure 1 shows the results of the modulus of rupture. The highest MOR was achieved by the samples of the reference variant, made with industrial melamine-urea-formaldehyde resin, i.e. 39.8 N/mm². The lowest MOR was achieved by variant 12, i.e. 15.2 N/mm². Analyzing the graph below, one can see the dependence of the increase in MOR with an increase in the proportion of soybean starch, starting from 23.4 N/mm² for variant 10 to 34.5 N/mm² for variant 20. Comparing the MOR results with the density profile data (Figure 5), one can observe a significant relationship between the density of the outer layers and the MOR of the panels. Analysis of the graph shown in Figure 5 shows that the highest increase in the density of the outer layers is achieved by variant 20, starting from 820 kg/m³ to 1010 kg/m³, which also has a high MOR. As confirmed by other researchers (Gumowska and Kowaluk, 2023), increasing the starch binder content significantly improves the MOR results, from 31.35 N/mm² to 40.10 N/mm². The obtained values, with the exception of variant 12, are higher than the requirements of EN 622-5: 2010. It is worth mentioning that according to the requirements of PN 622-5, for MDF-type boards with a thickness of 2.5 mm to 4 mm, the MOR is 23 N/mm².

Considering the statistical analysis, there are statistically significant differences between the average values of the MOR results.

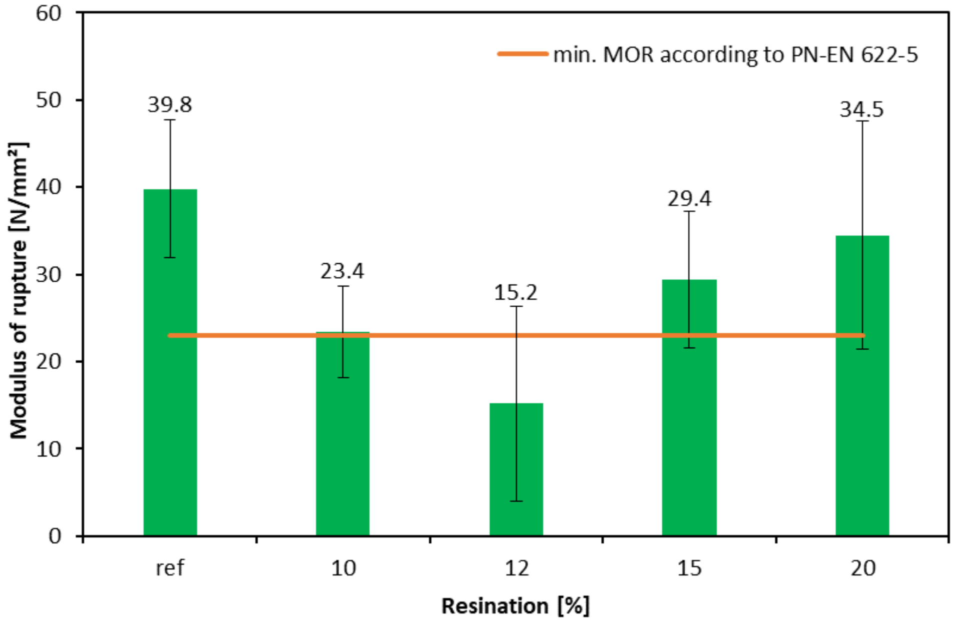

Figure 1. Modulus of rupture (MOR) of the tested panels

Modulus of elasticity

The test results for the modulus of elasticity are shown in Figure 2. Analyzing the graph, it can be seen that as the proportion of soy increases, the values of MOE increase. The highest value of 3666 N/mm² was obtained by the reference variant. The lowest MOE results were observed in variant 12, i.e. 1649 N/mm². According to Gumowska and Kowaluk (2023), an increase in binder content contributes to an increase in the value of MOE. According to the statistical analysis, there are statistically significant differences between the average values of the MOE results.

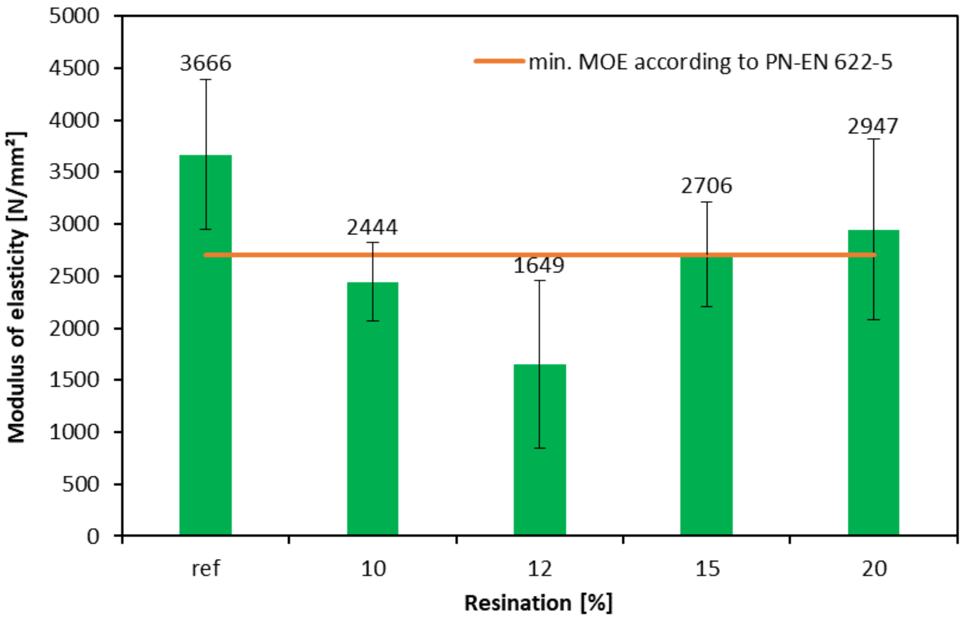

Figure 2. Modulus of elasticity (MOE) of the tested panels

Screw withdrawal resistance

Figure 3 shows the results of determining screw withdrawal resistance. Analyzing the values, it can be seen that the highest resistance was achieved by the samples of the reference variant. The smallest resistance was achieved by variant 10. Analyzing the graph below, it can be seen that with an increase in the proportion of soy binders, there is an increase in SWR, starting from 93 N/mm for variant 10 to 129 N/mm for variant 20. The results of variants 12, 15 and 20 samples are similar to each other. All the obtained average values for SWR are statistically significantly different from the variant 10. Hong et al. (2017) confirmed the theory that as the density of fiberboard increases and the binder content increases, the resistance to SWR.

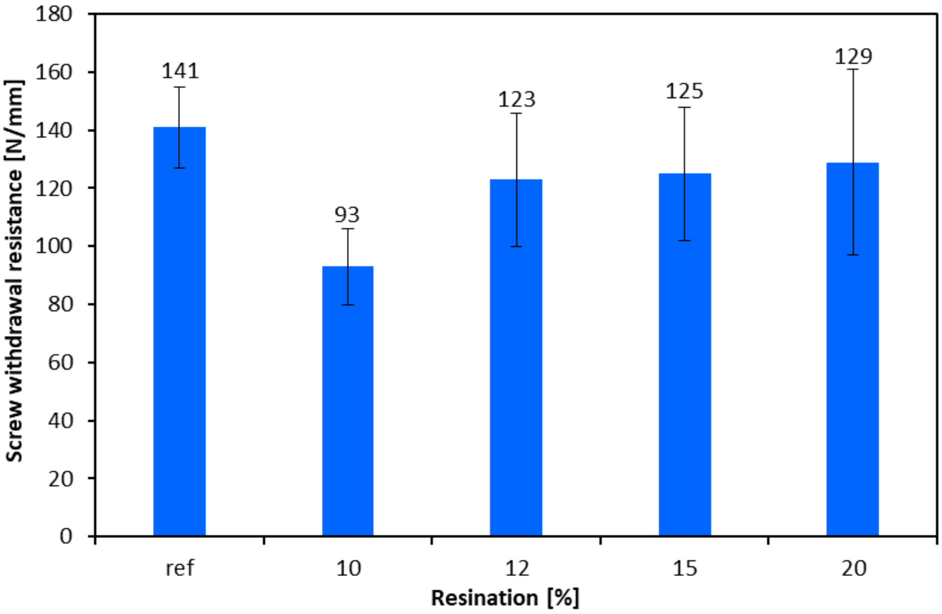

Figure 3. Screw withdrawal resistance (SWR) of the tested panels

Internal Bond

The internal bond values for the tested panels are shown in Figure 4. As can be seen from the data presented, the highest IB value was obtained by variant 10, i.e. 0.95 N/mm². The lowest IB value is characterized by the samples of variant 20, with a value of 0.20 N/mm². Analyzing the graph below, one can see the dependence of the IB decrease with the increase in the proportion of soybean binder, starting from 0.95 N/mm² for variant 10 to 0.20 N/mm² for variant 20. According to the literature, the density in the middle zone of the panels has a significant impact on the IB results. According to Wong et al (2000), the higher the density in the middle zone, the higher the IB. Another factor affecting IB values is the amount of water sprayed (Sala and Kowaluk, 2020). The results obtained, with the exception of variants 15 and 20, are higher than the requirements of EN 622-5:2010. It is worth mentioning that according to the requirements of EN 622-5, for MDF-type boards with a thickness of 2.5 mm to 4 mm, the minimum IB value is 0.65 N/mm². According to the statistical analysis, there are statistically significant differences between the average IB values.

Density profiles

The results of the density profile test are illustrated in Figure 5. The graph shows the results of one sample from each variant, since, as determined during the analysis of the results, the values obtained in the series of tests are similar to each other. Analyzing the graph below, it can be seen that the density of the surface layers is higher compared to the middle layer.

The highest density value was achieved by variant 15, i.e. 1021 kg/m³ for a thickness of 0.56 mm. Analyzing the graph, it can be noted that variant 15 also has the largest difference between the middle zone and the outer layers.

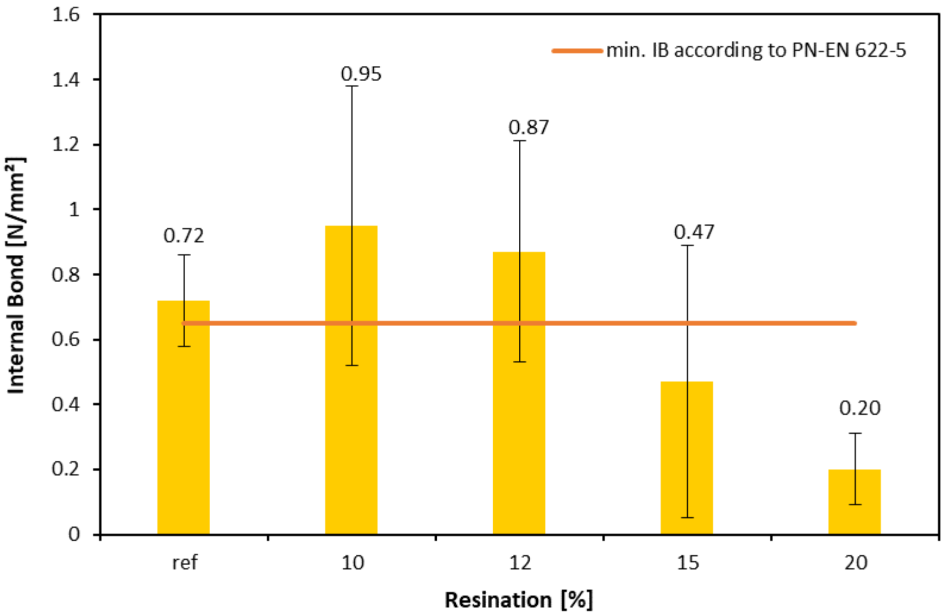

Figure 4. Internal Bond (IB) of the tested panels

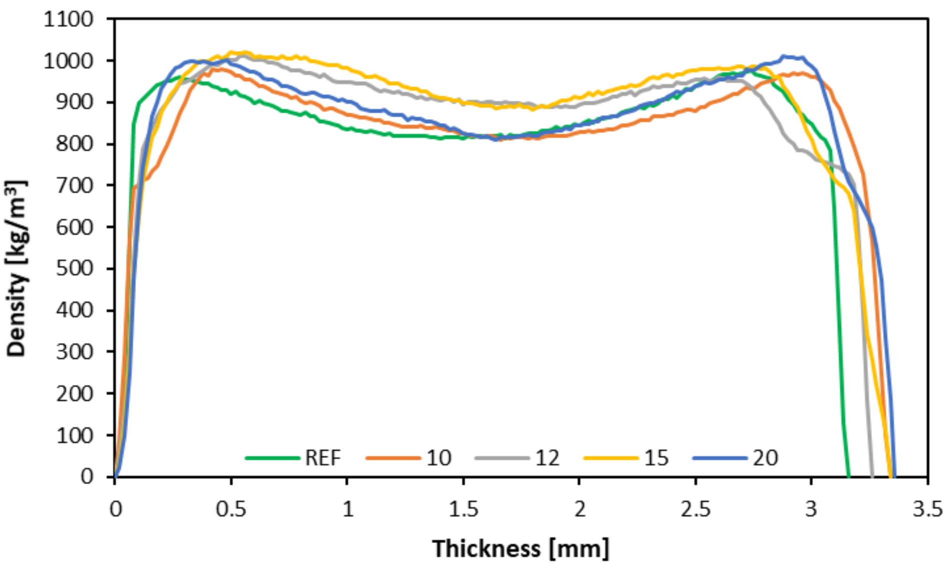

Figure 5. Density profiles of tested panels

Thickness swelling

The results of the thickness swelling tests are shown in Figure 6. The determinations were made after the 2-hour and 24-hour soaking of the samples in water. Analysis of the graph shows that the highest TS was formed after 24-hour soaking in water of variant 12. The lowest TS value was reached by the reference plates. Variant 12 reached more than 47% higher value TS after a 24-hour soaking compared to the reference variant. Analyzing the graph, it can be seen that the TS of the tested samples increased with the mass increase of soybean starch.

A different relationship was studied by Wronka et al. (2020) when studying hardboard with a starch binder. They observed a decrease in TS with an increase in the plant binder (starch). According to the requirements of PN 622-5, for MDF-type boards from 2.5 mm to 4 mm thick, the value of maximum TS is 35%. All the average TS values obtained are statistically significantly different from the others.

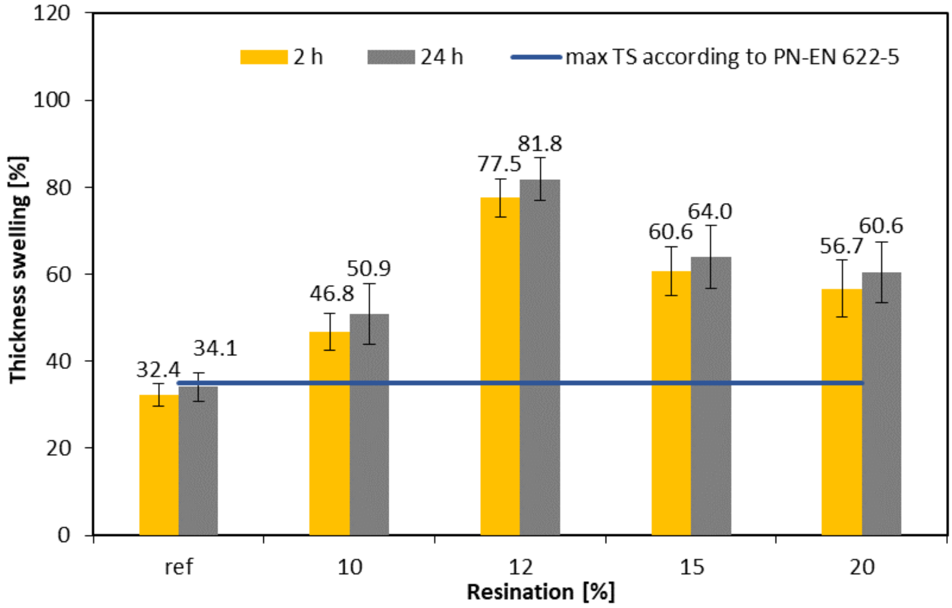

Figure 6. Thickness swelling (TS) of the tested panels

Water absorption

The results of water absorption are shown in Figure 7. The determinations were made after 2 and 24 hours of soaking the samples in water. Analysis of the graph shows that the highest WA after 2 and 24 hours of soaking was obtained by variant 12. The lowest WA was examined in the reference variant.

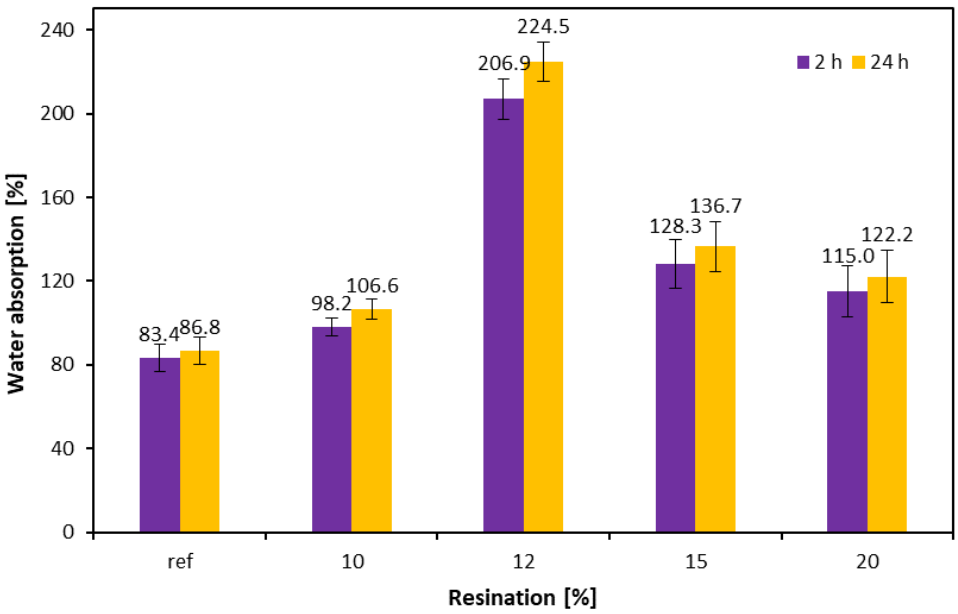

Figure 7. Water absorption (WA) of the tested panels

Based on the results, it can be concluded that a mass increase in soybean starch content causes a significant increase in WA. Lower WA values were obtained when testing wood-based plastics bonded with tannin glue mixed with hexane diamine. Xu et al. (2023) found that as the hexane diamine content increases, WA values decrease. According to the statistical analysis, there are statistically significant differences between the mean WA values.

Surface water absorption

The results of the surface absorption tests are shown in Figure 8. As can be seen from the graph, the highest amount of water was absorbed by the samples of variant 12, and the smallest amount by the samples of variant 20. Analyzing the graph below, one can see the dependence of the decrease in SWA values with an increase in the proportion of soybeans - with the exception of variant 12. A similar dependence of the decrease in SWA values was studied by Rosa and Kowaluk (2023) using a vegetable binder in a medium-density fiberboard. The obtained average SWA values are not statistically significantly different from the others.

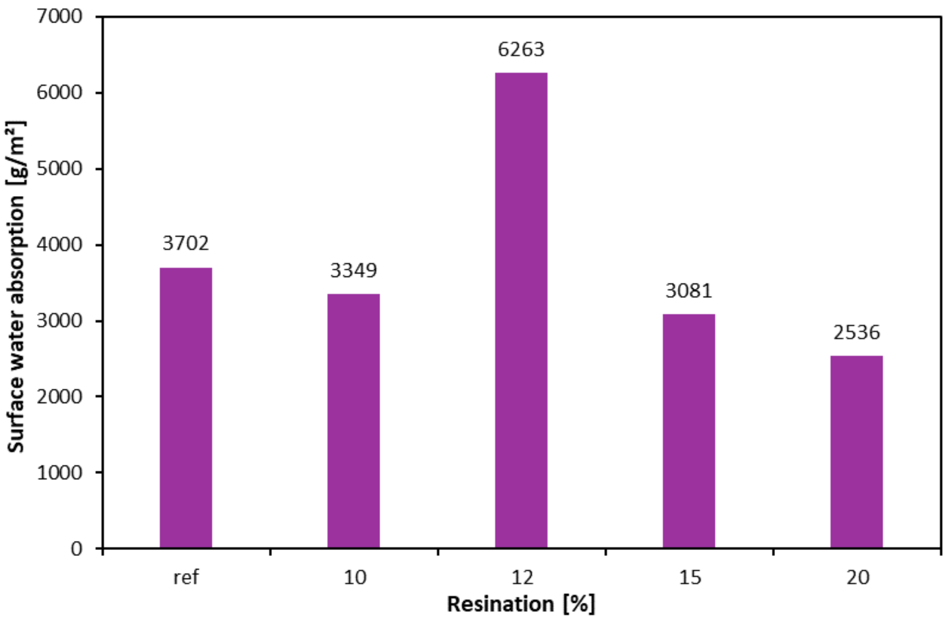

Figure 8. Surface water absorption (SWA) of the tested panels

CONCLUSIONS

Based on the research and analysis of the results, it can be formulated the following conclusions and observations:

- As the density of the outer layers increases, the modulus of rupture and modulus of elasticity values increase.
- Increasing the proportion of soybean starch in the panels increases the values of the modulus of rupture, modulus of elasticity and screw withdrawal resistance.
- As the proportion of soy starch increases, internal bond values decrease.
- Variant 15 has the largest difference between the core layer and the surface layers.
- Thickness swelling and water absorption values increase with a mass increase in the proportion of soybean starch in the panels.
- Surface water absorption values, except for variant 12, decrease with increasing soy binder.

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Streszczenie: *Zastosowanie skrobi sojowej jako spoiwa w technologii płyt HDF.* Celem badań było określenie wybranych właściwości płyt pilśniowych suchoformowanych o wysokiej gęstości (HDF) spajanej mąką sojową jako przyjaznym dla środowiska spoiwem. Zakres prac obejmował produkcję płyt w warunkach laboratoryjnych o różnym udziale masowym mąki sojowej tj. 10%, 12%, 15% i 20%. Określono wybrane właściwości mechaniczne i fizyczne płyt, a mianowicie wytrzymałość na zginanie, moduł sprężystości przy zginaniu, opór przy osiowym wyciąganiu wkrętów, wytrzymałość na rozciąganie prostopadłe, profil gęstości, spęcznienie na grubość, nasiąkliwość i absorpcję powierzchniową wodną. Wyniki wykazały, że zwiększenie udziału masowego spoiwa sojowego przyczynia się do poprawy wybranych właściwości mechanicznych, natomiast pogarsza właściwości fizyczne.

Słowa kluczowe: płyta pilśniowa, HDF, soja, spoiwo, właściwości fizyczne, właściwości mechaniczne

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