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The use of coffee bean post-extraction residues as a filler in plywood technology

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Abstract: *The use of coffee bean post-extraction residues as a filler in plywood technology*. The aim of the research was to determine the influence of post-extraction coffee beans used as a glue mass filler for the plywood glue joint on their selected mechanical and physical features. In the scope of the research the plywood of different content of post-extraction coffee beans in glue mass have been produced in laboratory conditions, as well, as reference material, the plywood with wheat flour as a glue mass filler have been made. The investigated material has been tested according to different features, including measurement of the plywood density profile, static bending strength and modulus of elasticity, shear strength, water absorption, as well as resistance to axial removal of screws. The significant reduction of bending strength, modulus of elasticity when bending, shear strength, as well as resistance to axial removal of screws has been found for samples with coffee bean residues, when referred to reference plywood. Also, decreasing penetration depth of coffee residues filled glue mass has been noted, with the coffee bean post-extraction residues content raise.

Keywords: plywood; filler; density profile; static bending strength; perpendicular tensile strength; water absorption

INTRODUCTION

According to PN-EN 313-1:2001 and PN-EN 313-2:2001 standards, plywood is a material consisting of odd number of layers. The fibres in all the layers are parallel to one other. Physical and mechanical properties depend on the type of wood, quality of veneer, thickness, type of adhesive and gluing method. Also it is depend on type of filler which is used. Most commonly used organic fillers are wheat flour (Mamiński and Sedliacik 2016, Yang and Frazier 2016), lignin (Vázquez *et al.* 1995, Vázquez *et al.* 1999, Aziz *et al.* 2019), potato starch and woodflour. Fillers are used to increase viscosity and reduce costs. Veneered surface is porous so a filler is needed to help cover all surface and prevent resin from penetration of into deep in material (Pizzi 1994). Also, fillers improve the bonding interaction between wood and adhesive mass.

There was a quite broad range of research on new products which could be used as a filler in adhesive mass. One research explored the use of modified woodflour as a thermoset filler in the context of its mechanical features (Marcovich *et al.* 2000). Tests of composites made with different degrees of esterification of wood particles after water absorption show that they are more hydrophobic than the untreated samples. Hand *et al*. (2018) investigated the chemical bonding between soy flour and phenol-formaldehyde (PF) resin during hot-pressing. Soy components do not have much influence on the curing process, and the chemical bonding was minimal. The same type of organic filler was used in tests completed by Buddi *et al.* (2018). The main part of this research was to classify the best process parameters for plywood manufacturing using a soy flour adhesive. The test results show that the modulus of rupture is decreasing for samples with a soy filler. In another research, by Ong *et al.* (2018), palm kernel flour was used as a filler in plywood technology. Tests were carried out to analyse shear strength and formaldehyde emission of plywood; the value of shear strength increased significantly – in these tests from 0% to 13% – after adding a filler to the adhesive mass. The situation changed after adding more filler. Shear strength value start decreasing from 23% of filler addition. In research of Kumar *et al.* (2013) the activated charcoal was added in the urea-formaldehyde (UF) resin. The researchers found out that the activation energy of tested resin decreases with raising charcoal concentration; that means the UF glue mass modified that way will cure at a lower temperature. According to Krzysik (1975), the charcoal particles have a large specific surface. This feature of charcoal has been successfully applied by Kowaluk *et al.* (2016) in particleboards production as a formaldehyde scavenger. Some promising results of the application of alumina nanoparticles as a filler to PF resin and plywood production were reached by Zhang *et al.* (2018). The researchers found that after adding a proper amount of alumina nanoparticles (2% by weight), the curing rate and the bonding strength of resin raises significantly.

The coffee grain is a material with slightly acidic pH of around 6. Due to citric, phosphoric, apple, acetic and tartaric acid content, they affect the acidity of coffee. Post-extraction coffee beans contain 2.28% of nitrogen, 0.06% phosphorus and 0.6% of potassium. These materials are very often used in gardening or as a beauty care product (Chalker-Scott 2016). No prior attempts to apply coffee post-extraction grains in gluing have been found.

The aim of the research was to determine the influence of post-extraction coffee beans content used as a glue mass filler for the plywood glue joint on their selected mechanical and physical features.

MATERIALS AND METHODS

Research material

The tested material was plywood produced with the use of different glue mass. The reference glue mass was a mixture of following ingredients: melamine-urea-formaldehyde (MUF) resin of 65% solid content, 20% w/w aqueous solution of $(NH_4)_2SO_4$ as a hardener, wheat flour as an industrial filler, and water. The weight ratios of ingredients were as follow: 100:8:10:5, resin : hardener : filler : water, respectively. The coffee residues, taken from a local coffeehouse as a post-extraction particles of *Coffea arabica* L., used in research have been completely dried, milled and sieved through a 0.1 mm size mesh prior to their addition to the glue mass. The following plywood types have been produced and tested under the laboratory conditions: 0, 1, 5, 10, 10F and 20, where the numbers indicate the content (w/w) of the coffee filler in the glue mass, and 10F means the plywood produced with the use of 10 w/w addition of industrial filler (wheat flour – reference plywood). Prior to the preparation of the plywood, the curing time of the prepared glue mass was measured on two samples of every glue mass. The measurement was performed at a water temperature of 100°C. The established curing time was as follow: 50 s for 0 plywood type, 55 s for 1 and for 10F plywood type, 70 s for 5 plywood type, 90 s for 10 plywood type and 112 s for 20 plywood type. On the basis of the achieved results, the pressing time for the preparation of the research material (plywood) was fixed as 360 s. The veneers used in the research were of pine (*Pinus sylvestris* L.) wood, 1.5 mm thick, industrially rotary cut, with 5.5% moisture content. Compositions of 3 layers (veneers) were applied. The application of glue mass was 180 g/m^2 of bonding line, constant. The pressing temperature was 140°C and the specific maximum pressure was 1.5 MPa.

Static bending strength and modulus of elasticity

12 samples (dimensions – 150 mm length x 50 mm width x thickness) of each tested plywood type have been investigated in accordance with PN-EN 310 standard to evaluate the modulus of elasticity (MOE) and modulus of rupture (MOR) under static bending. The span between supports (3-point bending) was 100 mm. The test was carried-out on a computer-controlled universal testing machine.

Shear strength

8 samples of every plywood type was tested to measure the shear strength. The test was carried-out in accordance with PN-EN 205:2016 standard on a computer-controlled universal testing machine.

Screw withdrawal resistance

Tests of resistance to axial withdrawal of screws (SWR) from the produced plywood have been conducted in accordance with PN-EN 320:2011 standard. At least 7 samples of each plywood type were taken to complete the tests. The test was carried-out on a computer-controlled universal testing machine.

Water absorption

42 samples (dimensions – 50 mm x 50 mm x thickness; 7 samples per every plywood type) were tested in accordance with (soaking parameters) of PN-EN 317:1993 standard. Samples weight measurements were made at specified time intervals (2h, 24h of soaking). Water absorption (WA; %) was calculated as follows:

$$WA = \left(\frac{m_2 - m_1}{m_1}\right) \cdot 100\ [\%] \tag{1}$$

where: m_1 – sample weight before soaking [g], m_2 – sample weight after soaking [g]

Density profile

Density profile was tested on three samples of every tested plywood type (dimensions – 50 mm x 50 mm x thickness). The density profile test was carried out on a X-Ray density profile analyser DA-X (GreCon), the measurement method of which is based on X-rays. The sampling step was 0.02 mm. After the measuring of the profiles, every three samples of the same plywood type have been analyzed and the most representative profile was assigned for further evaluation (comparison to remaining tested plywood density profiles). Since the density profiles of plywood are symmetrical along the middle of the thickness, to better analyse the profiles, the half of the thickness of the tested panels were presented on the resulting plot.

Samples conditioning

All the tested samples have been conditioned prior to the testing in 20°C/65% RH to achieve the constant weight.

Statistical assessment

The achieved results of all the tested features, excluding density profile, have been evaluated statistically applying Fisher's exact test with probability level p=0.05, to establish whether the achieved average values are statistically equal. Where applicable, the mean values of the investigated features and the standard deviation, indicated as error bars on the plots, have been presented.

RESULTS

Static bending strength and modulus of elasticity

figure 1 presents the average values of modulus of elasticity of tested panels with different filler content. As can be seen, the highest MOE value of 12557 N/mm^2 can be found for plywood with no filler addition. In case of the reference 10F panel, the MOE value is about 4% smaller than the highest value. The lowest MOE value of 3645 N/mm^2 is found for the panel with the highest coffee filler content of 20% w/w. Due to the wide distribution of individual results in the range of particular plywood type, which are represented on the plot by the error bars, it is hard to find any dependence between the filler content and modulus of elasticity of the tested panels. In the light of the requirements of PN-EN 636+A1:2015-06 standard concerning MOE, the tested panels can be classified into the following classes: 0 – E120, 1 – E70, 5 – E100, 10 – E70, 10F – E120 and 20 – E40. The only statistically significant differences of the mean MOE values can be found for 0 and 10 and 20 panels, as well as between 10F and 20 panel.

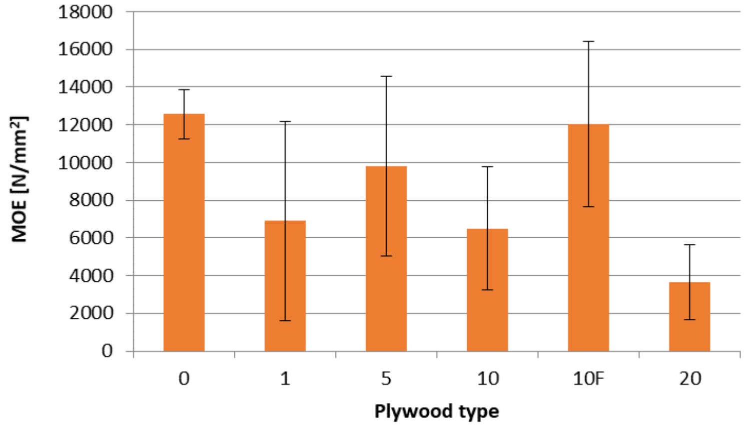

Figure 1. Modulus of elasticity of the tested panels

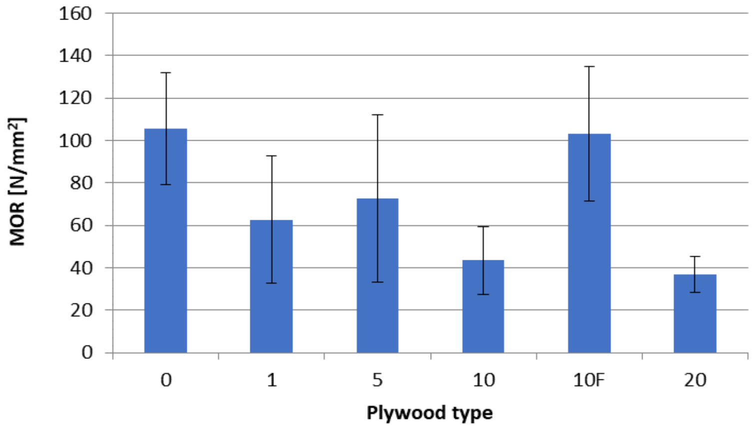

Figure 2. Modulus of rupture of the tested panels

The results of modulus of rupture measurement of the tested panels are presented in figure 2. It is evident that the distribution of the results is similar to the dependences between the properties of MOE. Also, the statistical analysis of MOR gives the same results. In the light of requirements of PN-EN 636+A1:2015-06 standard concerning MOR, the tested panels can be classified into the following classes: 0 – F70, 1 – F40, 5 – F40, 10 – F25, 10F – F60 and 20 – F20.

Shear strength

On the figure 3 the average values of shear strength of the samples of plywood of different filler content are presented.

As it can be seen, the highest value of shear strength – 1.66 N/mm^2 – was found for the reference plywood produced with the use of 10% w/w of the industrial (wheat) filler.

When analyzing the coffee filler samples only, the highest mean value of shear strength – 0.50 N/mm^2 – was recorded for plywood type 1, and the lowest value – 0.26 N/mm^2 – was recorder for plywood type 10. It is worth to add that the shear strength of plywood produced with the use of 10% of industrial filler (wheat flour) is over 330% higher than the highest value of shear strength when coffee filler is used.

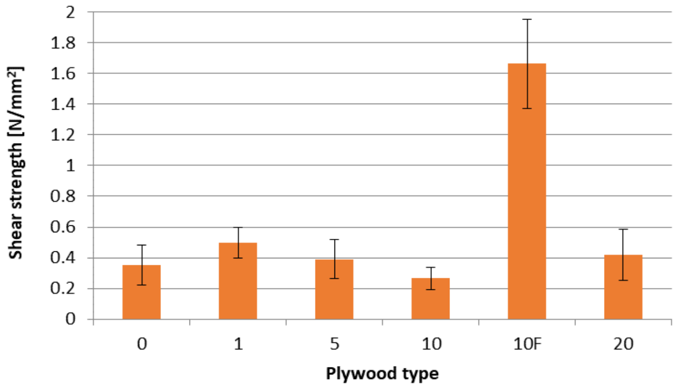

Figure 3. Shear strength of tested panels

The only statistically significant differences of the mean values of shear strength can be found between 10F and the remaining plywood types, as well as between types 1 and 10.

Screw withdrawal resistance

The results of the tests of resistance to axial withdrawal of screws (SWR) from the produced plywood are presented in figure 4.

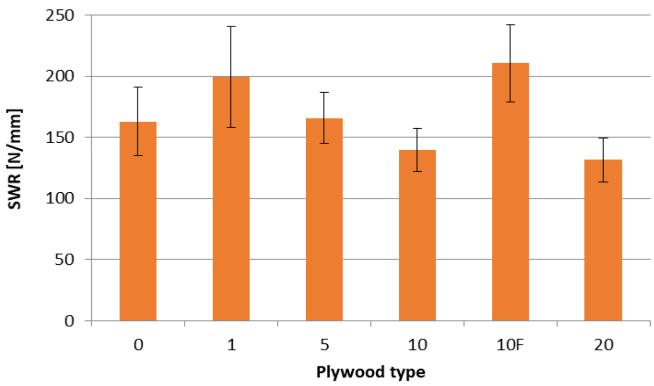

Figure 4. Screw withdrawal resistance of tested panels

As is evident from the graph above, the highest value of screw withdrawal resistance, 210.7 N/mm, has been found for 10F plywood type, when the lowest value, 131.7 N/mm for panel 20. When analyzing the panels with coffee filler content only, it can be concluded, that with the increase of filler content from 1 to 20% w/w, the screw withdrawal resistance decreases for about 34% in regard to the highest value. The decrease of the SWR values with raised coffee filler content can be connected to the smaller densification of veneers, which is visible on figure 6, where the density profiles are presented. The statistically significant differences of mean values can be found between panels 10 and 20 in regard to the remaining plywood types.

Water absorption

The average values of water absorption of the tested plywood with different filler contents, when soaked in water, are presented in figure 5.

It is clear that there is no strong connection between water absorption and filler content of the tested panels. Such a neutral influence of the glue filler (soy flour) on the properties of produced OSB panels was documented by Hand *et al.* (2018). The highest average value of water absorption reached by the plywood type 1 was 59.6% after 24 h of soaking. The lowest weight of water after 24 h of soaking was noted for panel 5 – 48.5%. It should be noted that with the increase of coffee filler content, the standard deviations, presented on the plot as the error bars, increases. This indicates different values of water absorption for individual samples. This can be caused by uneven distribution (thus, different efficiency) of the coffee filler. Such a problem with acceptable dispersion of various vegetal fillers, like sawdust, woodflour, sisal, bagasse, has been indicated by Marcovich *et al.* (2000).

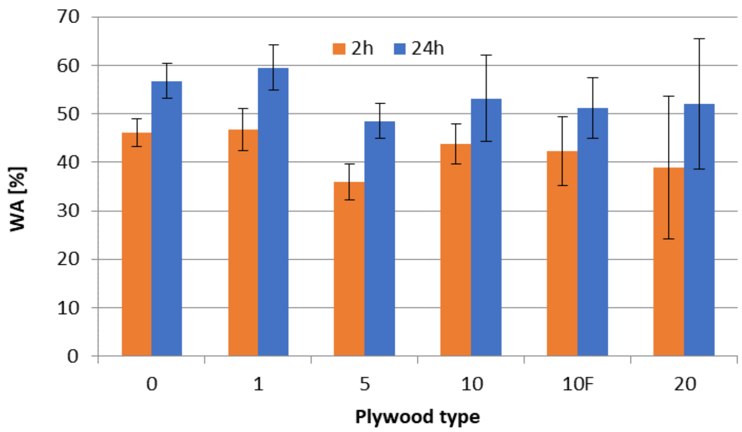

Figure 5. Water absorption of tested panels after 2 and 24h of soaking in water

According to the statistical analysis, the only statistically different average value after 2h of soaking is plywood 5 in regard to panels 0, 1 and 10. There is no statistically significant difference of mean values achieved after 24 h of soaking.

Density profile

The density profiles of the tested panels was presented on figure 6. The mean density of the veneers in plywood structure located on the face layers is between 620 and 730 kg/m^3, and the highest density (the bonding line) is about 1200 kg/m^3.

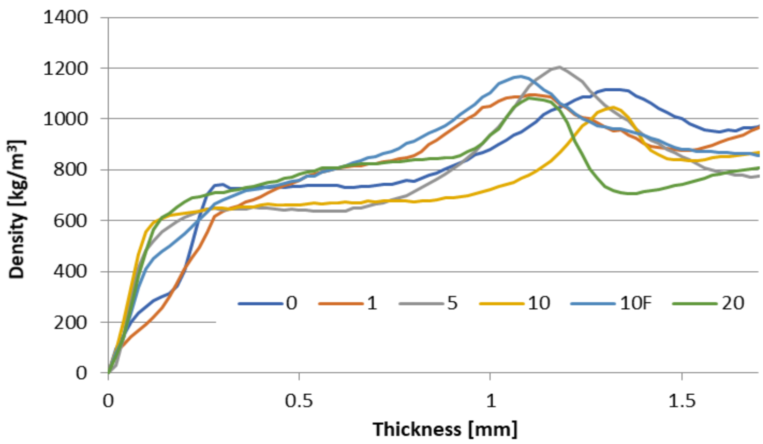

Figure 6. Density profiles of tested panels

It can be seen that there is a general difference between the evaluated profiles: with an increase of the filler content, the peak of density, located on 0.8–1.4 mm panel thickness, becomes narrower. The mentioned peak density represents the bonding line presence. The narrower peak density with increased filler content can be explained by the function of the filler, which is reduction of glue mass soaking into the veneer. Since the filler content increases, the reduction of glue mass penetration to the wood structure is observed on the density profiles (reduction of densification).

CONCLUSIONS

According to the conducted research and the analysis of the achieved results, the following conclusions have been drawn:

1. The mechanical properties of the plywood produced with the use of coffee flour as a glue mass filler, in the amount of 1–20% by weight, like modulus of elasticity and modulus of rupture, are significantly lower that the mentioned properties of plywood produced with no filler addition or with an addition of 10% w/w of wheat flour (industrial).
2. There is no significant influence of the coffee filler content in the plywood glue mass in the range of 1–20% w/w on the shear strength; however, the shear strength of plywood produced with the use of 10% of industrial filler (wheat flour) is over 330% higher than the highest value of shear strength when a coffee filler is used.
3. The coffee filler content increased from 1 to 20% w/w causes a decrease of screw withdrawal resistance by about 34% in regard to the highest value.
4. There is no significant influence of the coffee filler, for a content range from 0 to 20% w/w, on water absorption of the produced plywood. However, with an increase of the filler content, the distribution of water absorption amount increases.
5. The increase of coffee filler content causes the reduction of glue mass penetration into the veneer structure.

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Streszczenie: *Wykorzystanie pozostałości poekstrakcyjnych ziaren kawowca jako wypełniacza w technologii sklejek.* Celem badań było określenie wpływu różnego udziału pozostałości poekstrakcyjnych ziaren kawowca, zastosowanych jako wypełniacz w masie klejowej w technologii sklejki, na wybrane właściwości sklejki. W zakresie badań zostały wytworzone sklejki w warunkach laboratoryjnych z różnym udziałem pozostałości poekstrakcyjnych ziaren kawowca w postaci mączki, jako wypełniacza w masie klejowej. Wytworzono również sklejki referencyjne, do których wytworzenia zastosowano mąkę pszenną jako wypełniacz w masie klejowej. Powstałe próbki zostały scharakteryzowane pod kątem ich wybranych właściwości fizycznych i mechanicznych. Przeprowadzone zostały badania profilu gęstości, wytrzymałości na zginanie statyczne i modułu sprężystości przy zginaniu, wytrzymałości na ścinanie przez rozciąganie, nasiąkliwości oraz oporu przy osiowym wyciąganiu wkrętów. Zauważono istotny spadek badanych wytrzymałości w porównaniu do wytrzymałości próbek referencyjnych (z mąką pszenną jako wypełniaczem masy klejowej). Odnotowano znacznie mniejszą penetrację masy klejowej w głąb struktury fornirów wraz ze wzrostem udziału badanego wypełniacza.

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