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Properties of Hybrid Plywood Produced by Utilisation of Peeler Cores

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Abstract: The aim of this research work was to investigate the feasibility of upcycling poplar (*Populus* spp.) peeler cores as a by-product from the production of plywood in manufacturing lightweight hybrid poplar and beech plywood panels, containing different ratios (60%, 80%, and 100%) of peeler core sections in the core layer. This corresponds to effective percentages of panel surface glued with peeler core slides of 80%, 64%, and 48%, respectively. The physical properties (density, water absorption, and thickness swelling) and mechanical properties (bending strength (MOR) and modulus of elasticity (MOE)) of the laboratory-fabricated hybrid panels were determined in accordance with the applicable European standards (EN 310, EN 317, and EN 323). The highest MOE and MOR values of 3575 N·mm^{-2} and 28.1 N·mm^{-2}, respectively, were obtained for the hybrid poplar plywood panels with a thickness of 20 mm and 100% peeler core sections. The use of beech veneer in the face layers did not lead to a significant increase in the mechanical properties. In this case, the MOE and MOR values of the hybrid plywood panels with a thickness of 20 mm and 80% peeler core sections were 5954 N·mm^{-2} and 35.2 N·mm^{-2}, respectively.

Keywords: beech; lightweight panel; peeler core; physical and mechanical properties; poplar; veneer

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1. Introduction

The increasing global demand for wood and wood-based products by the furniture and construction industries leads to a significant consumption of wood raw materials. The use of fast-growing tree species and the efficient valorisation of alternative lignocellulosic raw materials, such as agricultural biomass and recycled wood, in the production of wood-based panels represent viable and environmentally friendly approaches to address this problem [1].

Due to its numerous favourable characteristics, such as durability, resistance to deformation, and excellent tensile strength, plywood is one of the main layered wood-based materials, widely used in furniture manufacturing, interior design, construction, packaging, etc. [2,3]. The main type of veneer used to produce plywood, glue-laminated details, and other types of laminated wood is rotary cut (peeled) veneer. These products are primarily applied in structural construction, roofing and flooring, the automotive industry, and aviation, as well as in furniture production.

In recent years, the furniture industry has begun to aim to use lightweight panels that have high mechanical characteristics [4]. Modern technologies for producing wood-based panels allow the use of small-sized and lower-quality wood raw materials; however, the wood consumption is significant. The production of so-called lightweight furniture panels minimises the application of wood resources and reduces carbon emissions. Currently, there is no standard classifying lightweight panels depending on their density. Among the specialists in the field, the following classification is generally accepted: lightweight panels have a density $\leq$ 500 kg·m^{-3}; very lightweight panels have density values $\leq$ 350 kg·m^{-3}; and ultra-lightweight panels are characterised by densities $\leq$ 200 kg·m^{-3} [5]. These panels also have some disadvantages, including their high price, which results in the increased cost of the final product, difficulty in processing with woodworking machines, poor edging quality, installation and fitting problems, etc. In general, lightweight panels can be manufactured entirely of light materials and multilayer panels that have outer layers made of high-density materials with high strength characteristics and inner layer(s) composed of lighter and lower strength materials [5].

Poplar wood is preferred for producing plywood due to its advantages of being a fast-growing wood species with a relatively low price, good workability and dimensional stability, environmental friendliness, a light color that facilitates dying, etc. In plywood manufacturing, poplar is often used as a substitute for the commonly used beech and birch wood [6–8]. Plywood manufacturing technology is associated with significant quantities of waste and by-products, such as peeler cores. It has been established that the volumes of waste peeler cores in the production of veneer and plywood vary from 1% to 30% depending on the average diameter of the logs [9–11]. At present, only a very small percentage of peeler cores is used for manufacturing value-added products [12,13], while the predominant part is mainly used for the production of energy, wood chips, and other applications with a low economic value, such as packaging, pallets, etc. Currently, there is no well-established approach for the effective and rational utilisation of these by-products of plywood manufacturing in the furniture and construction industries.

The aim of this research was to investigate the feasibility of using poplar peeler cores as a by-product of plywood production in the development of lightweight hybrid plywood panels and determine their main physical and mechanical properties in order to assess their suitability for application in the furniture and construction industries. A simplified method for cutting peeler cores as an alternative to other cutting methods described in our previous research was presented [12,13].

2. Materials and Methods

2.1. Materials

Five-layer hybrid plywood panels were fabricated in laboratory conditions using rotary cut veneers from two wood species, i.e., poplar (*Populus* spp.) and common beech (*Fagus sylvatica* L.), provided by the plywood factory Welde Bulgaria AD (Troyan, Bulgaria). The dimensional characteristics of the poplar and beech veneer were 600 mm $\times$ 600 mm $\times$ 2.2 mm and 550 mm $\times$ 550 mm $\times$ 1.2 mm, respectively. The determined moisture content of all veneer sheets was 8 $\pm$ 1 %. In this work, three experimental hybrid plywood panels were produced, in the front layers of which (layers 1 and 5), a veneer of beech wood was used, in the even layers (2 and 4), poplar veneer, and the core layer (3) sections were made of poplar peeler cores. The use of beech veneer in the face layers was aimed at improving the physical and mechanical properties of the hybrid plywood produced. The poplar peeler cores used, also provided by Welde Bulgaria AD, had an average length of 1.35 m and average diameter of 100 mm. The peeler cores were dried to a final moisture content of 8 $\pm$ 1%.

Two types of wood adhesives were used for bonding the hybrid plywood panels, i.e., a commercial phenol-formaldehyde (PF) adhesive (Prefere 14J350; Prefere Resins Romania SRL) with solid content of 50%, viscosity of 372 MPa.s at 20 °C, and a pH of 6.8, and urea-formaldehyde (UF) adhesive (Resina 401; Unicol S.R.L., Fontanelle, Italy) with solid content of 65% and a pH of 5.7.

2.2. Structure of Lightweight Hybrid Plywood

The peeler cores were cut to length using a circular saw with a cut width of 4 mm. The following thicknesses of the peeler core section were chosen: l_1 = 12 mm and l_2 = 22 mm. The sections with 12 mm thickness were used to fabricate a hybrid five-layer plywood with a nominal thickness of 20 mm; the sections with 22 mm thickness were used to manufacture hybrid plywood with a nominal thickness of 30 mm. The peeler core sections were intended to be used as a filler in the core layer of the panels, so the final thickness of the hybrid plywood depended mainly on the respective thickness of the sections (l_n). The method of cutting the poplar peeler cores into sections is shown in Figure 1.

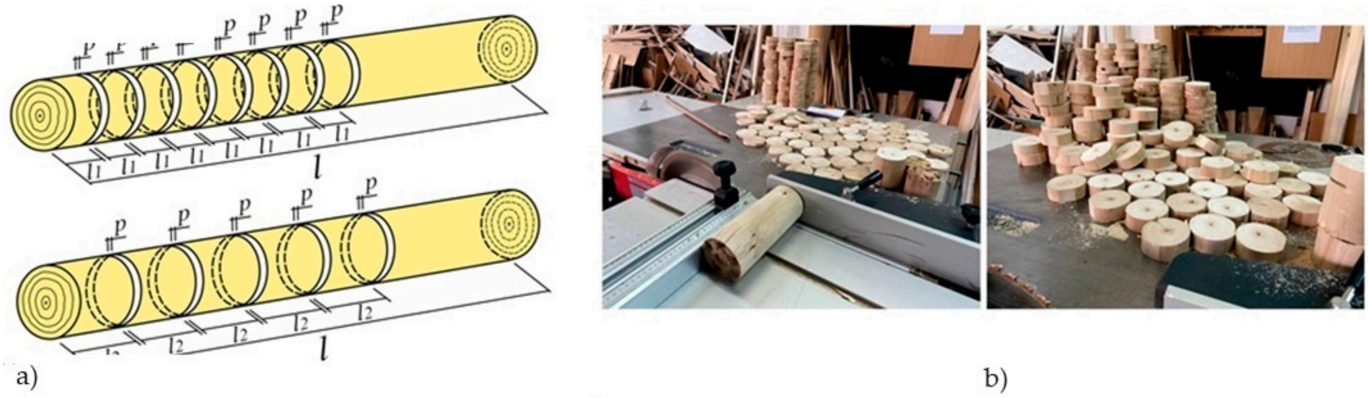


Figure 1. Cutting the peeler cores into sections: (**a**) graphical interpretation; (**b**) preparation of peeler core sections.

The number of peeler core sections in the core layer of the hybrid plywood panels depends on the maximum filling area of the veneers. A graphical representation of the method for producing the hybrid five-layer plywood is presented in Figure 2.

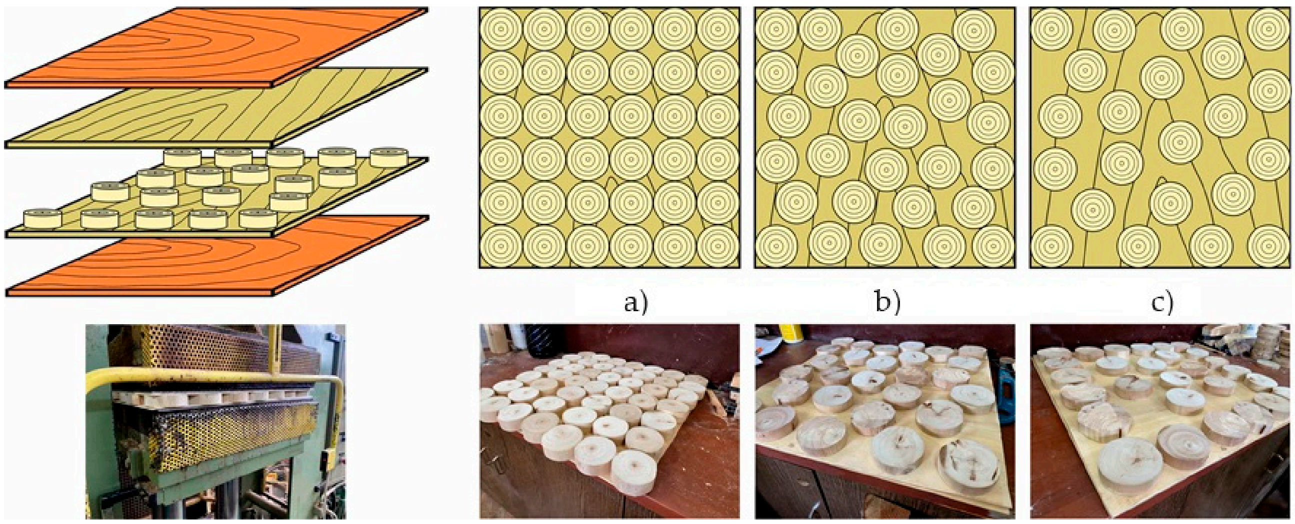


Figure 2. Lightweight five-layer hybrid plywood panels fabricated with different ratios of peeler core sections in the core layer: (**a**) 100%, (**b**) 80%, and (**c**) 60%.

In type (a), the goal was to fulfil maximum (100%) filling of the veneers with peeler core sections. The sections obtained were arranged tightly next to each other, leaving as little gaps as possible between them (Figure 2a). In this case, the maximum number of sections on the veneers with dimensions of 600 mm × 600 mm was 36 pieces. Type (b) aimed to reduce the sections to approximately 80% of the maximum number, i.e., 29 pieces. The number of peeler core sections in type (c) was reduced to approximately 60%, and the respective number of sections was 22. Thus, the effective percentages of the panel surfaces glued to the peeler core slides were 80%, 64%, and 48%, respectively.

According to the described methodology, 11 specimens of lightweight plywood were obtained. Their dimensional characteristics and the adhesive type used are presented in Table 1.

Table 1. Matrix of the experiment.

Panel Type	Face Veneer	Thickness, mm	Peeler Core Sections, %	Effective Percentage of Panel Surface Glued, %	Adhesive
Panel Type A	poplar	20	100	80	UF
Panel Type B	poplar	20	80	64	UF
Panel Type C	poplar	20	80	64	PF
Panel Type D	poplar	20	60	48	UF
Panel Type E	poplar	30	100	80	UF
Panel Type F	poplar	30	80	60	UF
Panel Type G	poplar	30	80	60	PF
Panel Type H	poplar	30	60	48	UF
Panel Type I	beech	18	80	60	PF
Panel Type J	beech	28	100	80	PF
Panel Type K	beech	28	60	48	PF

Due to the expected similar effect of the other factors (amount and thickness of peeler core sections), experiments with PF resin were repeated only for the boundary values. The aim was to compare the effect of PF and UF resins on the performance of the laboratory-made hybrid plywood panels.

The structure of the hybrid five-layer plywood panels, fabricated in the laboratory, was as follows:

- Panel Type A, B, C, and D (poplar/poplar/peeler cores/poplar/poplar)—2.2; 2.2; 12; 2.2; 2.2 mm;
- Panel Type E, F, G, and H (poplar/poplar/peeler cores/poplar/poplar)—2.2; 2.2; 22; 2.2; 2.2 mm;
- Panel Type I (beech/poplar/peeler cores/poplar/beech)—1.2; 2.2; 12; 2.2; 1.2 mm;
- Panel Type J (beech/poplar/peeler cores/poplar/beech)—1.2; 2.2; 22; 2.2; 1.2 mm;
- Panel Type K (beech/poplar/peeler cores/poplar/beech)—1.2; 2.2; 22; 2.2; 1.2 mm.

2.3. Gluing and Producing

The bonding of the hybrid plywood produced only from poplar wood was performed with UF and PF adhesives under hot pressing. The amount of UF adhesive used was 180 g.m^{-2} at a temperature of 150 °C and the pressing time was 5 min for all panels, regardless of their final thickness. The applied pressing pressure was 0.9 MPa. The selected hot-pressing parameters were selected on the basis of preliminary experiments for manufacturing hybrid plywood panels. During gluing, insufficient pressing contact between the two veneer sheets was observed in the area of the gaps formed between peeler core sections. This was clearly expressed when the ratio of sections in the core layer was decreased to 80% and even more noticeable at the 60% ratio of sections (Figure 3a).

For this reason, gluing tests were also carried out with PF adhesive at a spread rate of 170 g.m^{-2}. To avoid an area with gaps and blisters between the veneer sheets, they were initially glued two by two (Figure 3b). The pressing temperature was 125 °C. The applied hot-pressing pressure for the panels fabricated only from poplar veneers was 0.9 MPa, and the pressure was increased to 1.0 MPa for the plywood panels manufactured from beech and poplar veneers. The pressing time for the veneer sheets (two by two) was 2.5 min. The latter were additionally glued on one side only, and the peeler core sections were arranged and glued again by hot pressing. The pressing time for all panels was 6 min. The time was deliberately chosen to be longer than necessary to ensure the complete bonding of the paired veneer sheets and peeler core sections used in the core layer.

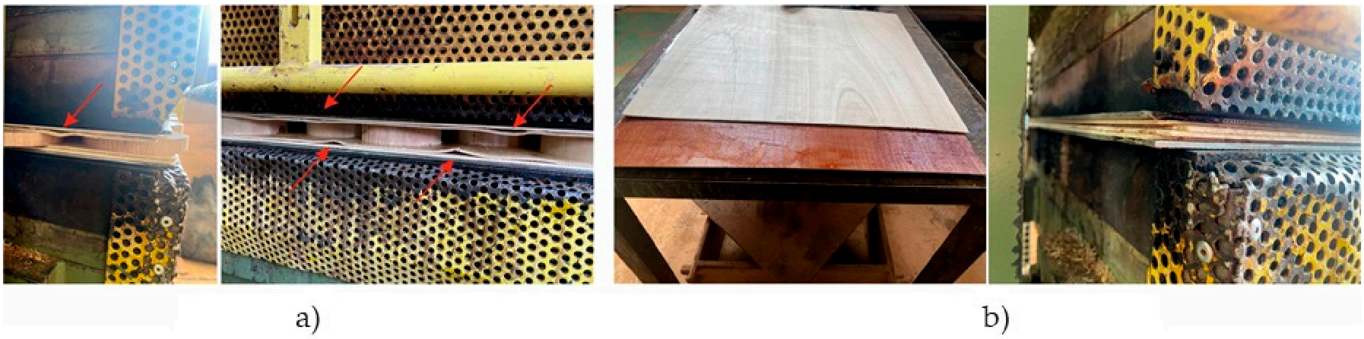


Figure 3. Hot pressing of lightweight hybrid plywood: (**a**) bonding areas with insufficient contact, (**b**) initial gluing with PF.

2.4. Physical and Mechanical Properties

The different types of hybrid plywood panels made entirely from poplar wood were fabricated with dimensions of 600 mm × 600 mm and various thicknesses, ranging from 20 mm to 40 mm. The dimensions of the panels produced with a combination of beech and poplar veneer sheets were 550 mm × 550 mm, with thicknesses of 18 and 28 mm.

The physical and mechanical properties were determined in laboratory conditions according to the European standards EN 317:1998, EN 323:2001, ISO 13061-2:2019, and EN 310:1999 [14–17]. The physical properties—density, thickness swelling (TS), and water absorption (WA) were established using Equations (1)–(3):

$$\rho_{mean} = \frac{m}{b_1 b_2 t} 10^6 \tag{1}$$

$$G_t = \frac{t_2 - t_1}{t_1} 100 \tag{2}$$

$$A = \frac{m_2 - m_1}{m_1} 100 \tag{3}$$

where

ρ is the panel's density, kg·m^{-3};
G_t is the thickness swelling after immersion in water, %;
A is the water absorption after immersion in water, %;
t_1 is the thickness before immersion in water;
t is the thickness of the test sample;
t_2 is the thickness after immersion in water;
b_1 and b_2 are the width and length of the test samples;
m is the mass of the test sample;
m_1 is the mass before immersion in water;
m_2 is the mass after immersion in water.

The modulus of elasticity (MOE) in static bending (E_m) and the bending strength (MOR) (f_m) of the laboratory-produced lightweight plywood were calculated using Equations (4) and (5).

$$E_m = \frac{l_1^3 (F_2 - F_1)}{4bt^3 (a_2 - a_1)} \tag{4}$$

$$f_m = \frac{3F_{max}l_1}{2bt^2} \tag{5}$$

where

E_m is the modulus of elasticity (MOE) in static bending, N·mm^{-2};

f_m is the bending strength (MOR), N·mm^{-2}.

Figure 4 shows working moments of testing the mechanical properties of the laboratory-fabricated hybrid plywood panels.

a)

b)

Figure 4. Determination of the mechanical properties: (**a**) hybrid plywood glued with UF, (**b**) hybrid plywood glued with PF.

The obtained values were processed using variational statistics, and the values between the two samples were processed using the *t*-test.

3. Results and Discussion

Minimal wood losses were found according to the accepted methodology for cutting the peeler cores into sections. The waste from this type of cutting resulted mainly in the form of shavings and two or three offcuts at either end of each peeler core. When cutting the peeler cores into sections with a thickness of 12 mm (Figure 1a), the quantitative yield reached 72%. When the peeler cores were cut into sections with thicknesses of 22 mm and 32 mm, the quantitative yields also increased to 78% (Figure 1b) and 80%, respectively. The results showed very low wood consumption—from 20 to 28%. However, these yields are significantly higher compared to other methods for the utilisation of peeler cores [12], and the technique is maximally simplified.

The physical properties of hybrid plywood panels fabricated with different ratios of peeler cores sections in the core layer are presented in Table 2.

The obtained results show that the density of the hybrid plywood panels varied between 304 and 378 kg·m^{-3}. These density values are significantly lower compared to conventionally produced poplar plywood [18–22]. The density decreased almost linearly with the decrease in the ratio of peeler core sections used in the core layer. There was a slight decrease in the density of the panels that had the same thickness and the same ratio of peeler core sections when replacing the UF adhesive (panel type B—313 kg·m^{-3}) with the PF adhesive (panel type C—309 kg·m^{-3}). This difference can be explained by the lower glue consumption when using PF resin.

Table 2. Physical properties of the hybrid plywood panels produced in this work.

Panel Type	Face Veneer	Thickness mm	Peeler Core Sections %	Adhesive	Density ρ_{mean}, kg·m^{-3}	Thickness Swelling G_t, %	Water Absorption A, %
Panel Type A	poplar	20	100	UF	344	1.0	25.3
Panel Type B	poplar	20	80	UF	313	1.1	25.1
Panel Type C	poplar	20	80	PF	309	1.2	26.0
Panel Type D	poplar	20	60	UF	304	1.1	24.8
Panel Type E	poplar	30	100	UF	355	0.9	24.7
Panel Type F	poplar	30	80	UF	343	0.9	23.6
Panel Type G	poplar	30	80	PF	319	1.0	28.9
Panel Type H	poplar	30	60	UF	310	1.0	22.5
Panel Type I	beech	18	80	PF	360	1.0	22.8
Panel Type J	beech	28	100	PF	378	0.9	23.2
Panel Type K	beech	28	60	PF	344	1.0	21.7

The use of beech veneers for the face layers (panel type I) resulted in increased density by 17% compared to the hybrid plywood panels fabricated from poplar (panel type C). Based on the results obtained, all of the types of hybrid plywood panels produced with peeler core sections in the core layer can be classified as lightweight panels [5].

The TS values (G_t) in all of the studied series of hybrid plywood were about 1%. These small values might be explained with the structure of the plywood panels produced, i.e., only 2 veneer sheets in the face layers. In addition, the wood fibre direction of the peeler core sections in the core layer of the panels was perpendicular to the panel plane [23].

The WA values of the hybrid plywood panels ranged from 21.7 to 28.9%. Generally, two types of trends were observed. Firstly, it was observed that plywood with lower peeler core sections exhibited generally lower water absorption. This phenomenon can be attributed to the reduced volume of wood materials per unit, leading to a smaller area exposed to water. Consequently, the decreased surface area exposure contributed to the observed lower water absorption in such plywood samples. Furthermore, plywood samples constructed with beech as face veneers demonstrated lower water absorption in comparison to those with poplar face veneers. This can be attributed to the higher density of beech as opposed to poplar, resulting in a more compact structure that limits the extent of water absorption in the plywood.

The summarised test results of the MOE and MOR values and the deformation behaviour of the laboratory-fabricated hybrid plywood types with a thickness of 20 mm are shown in Figures 5–7.

The obtained MOE values for all series of the hybrid plywood varied significantly (Figure 5). Notably, when determining the limit of the MOE and MOR values in the directions parallel and perpendicular to the direction of the wood fibres of the plywood, no significant differences were found. The number and location of the peeler core sections in the core layer of the panels played a substantial role in the mechanical performance. For this reason, the results of the mechanical characteristics in both directions (parallel and perpendicular) are summarised and presented together.

The highest MOE values were observed for panel type A—3088 N·mm^{-2}. The hybrid plywood of panel type B reached an average MOE value of 2659 N·mm^{-2}, or 14% lower compared to panel type A. When the UF adhesive (panel type B) was replaced by PF resin (panel type C), the average MOE values reached 2567 N·mm^{-2}, a slight decrease of 3%. The average MOE values for panel type D reached 2312 N·mm^{-2}; as expected, reducing the number of peeler core sections in the core layer of the hybrid plywood resulted in lower MOE values for all types of panels produced.

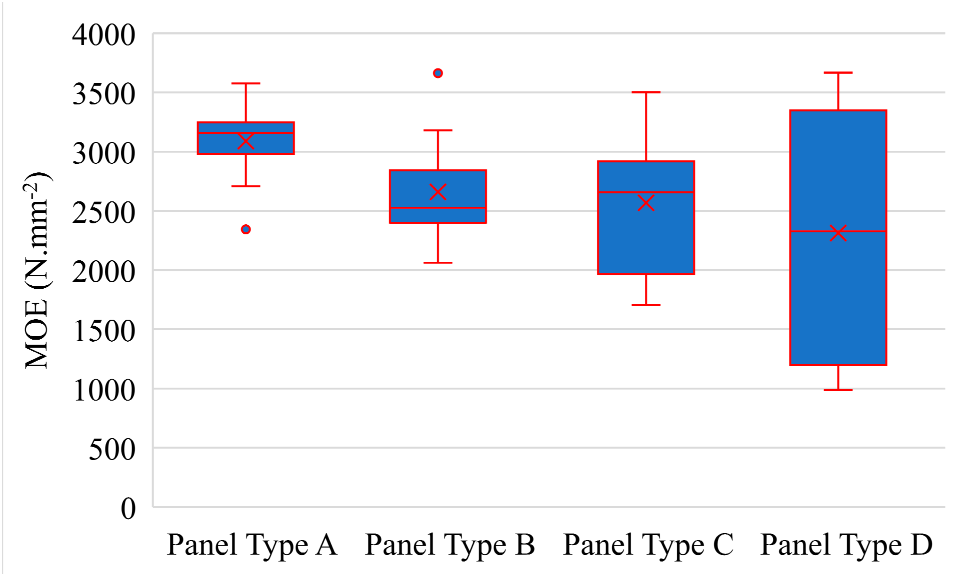


Figure 5. Modulus of elasticity (MOE) of hybrid plywood (20 mm thickness).

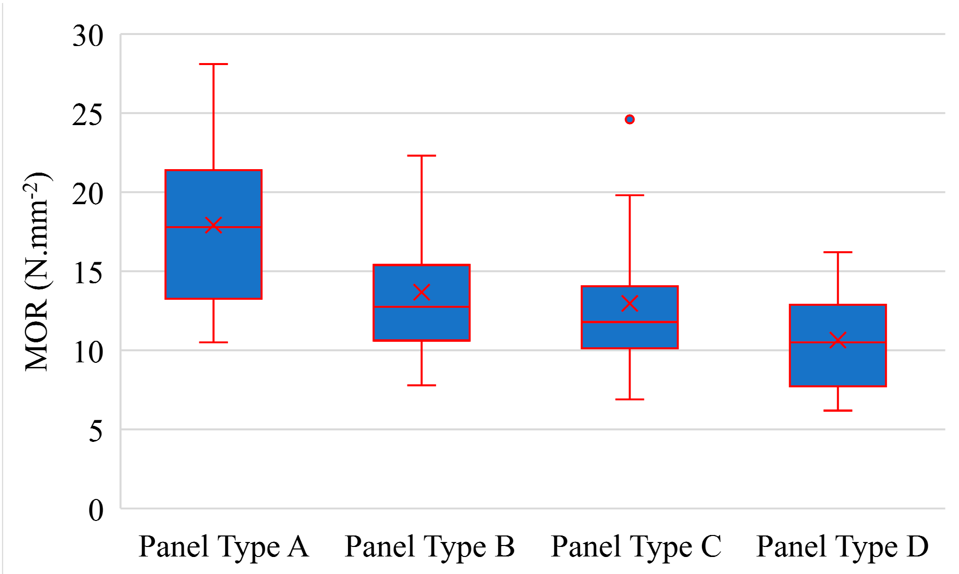
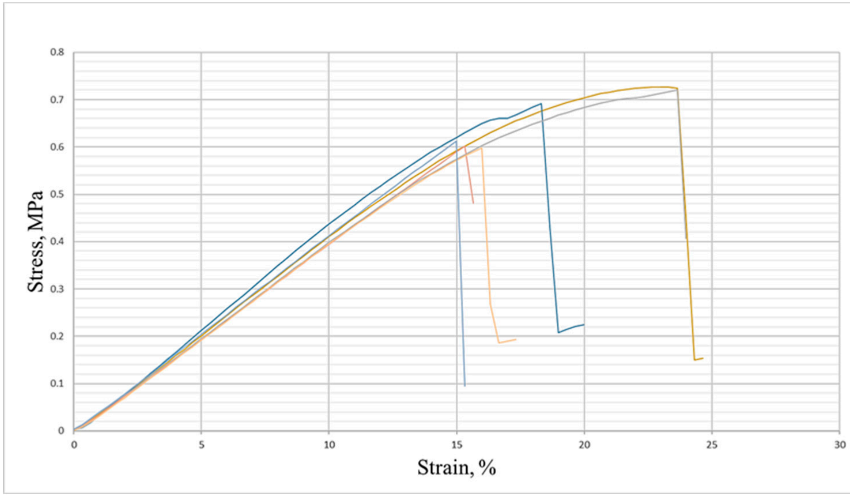


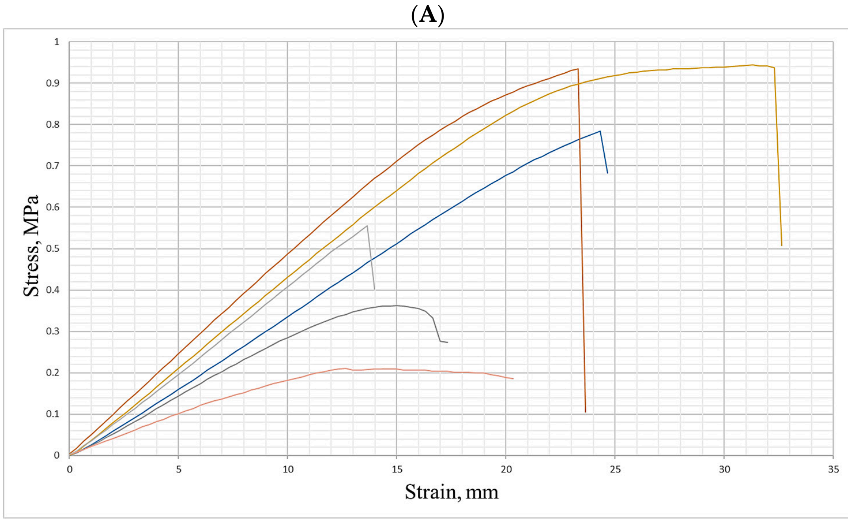
Figure 6. Bending strength (MOR) of hybrid plywood (20 mm thickness).

The determined MOE values for panel type D varied in a wide range from 986 to 3666 N·mm^{-2}. This might be attributed to small ratio (60%) of the peeler core sections used, leading to their non-uniform distribution in the core layer of the panels. Plywood samples featuring lower peeler core sections tend to exhibit increased voids due to the reduced filling area. These voids may serve as weak points, contributing to the initiation of failure during testing. Since the samples for the MOE were randomly selected, the occurrence of weak points under load is entirely unpredictable. Consequently, this randomness resulted in a wide range of values observed in the testing process.

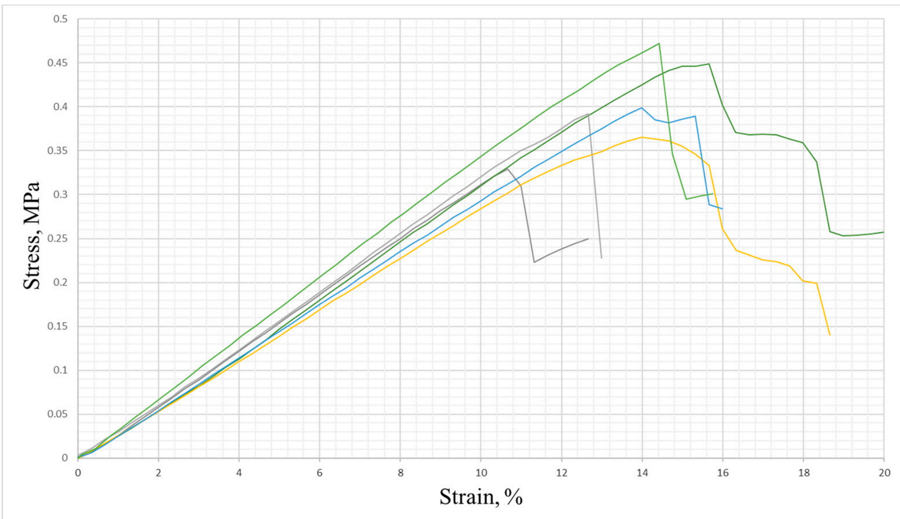
Markedly, the laboratory-made panels exhibited high stiffness values, relatively close to those of medium-density fibreboards (MDF), compared to conventional wood-based panels used in the furniture industry [24]. These high MOE values can be attributed to the structure of the core layer of the panels, i.e., the direction of the wood fibres of the peeler core sections was perpendicular to the plane of the plywood. This resulted in stresses close to splitting the wood rather than bending.



(**A**)

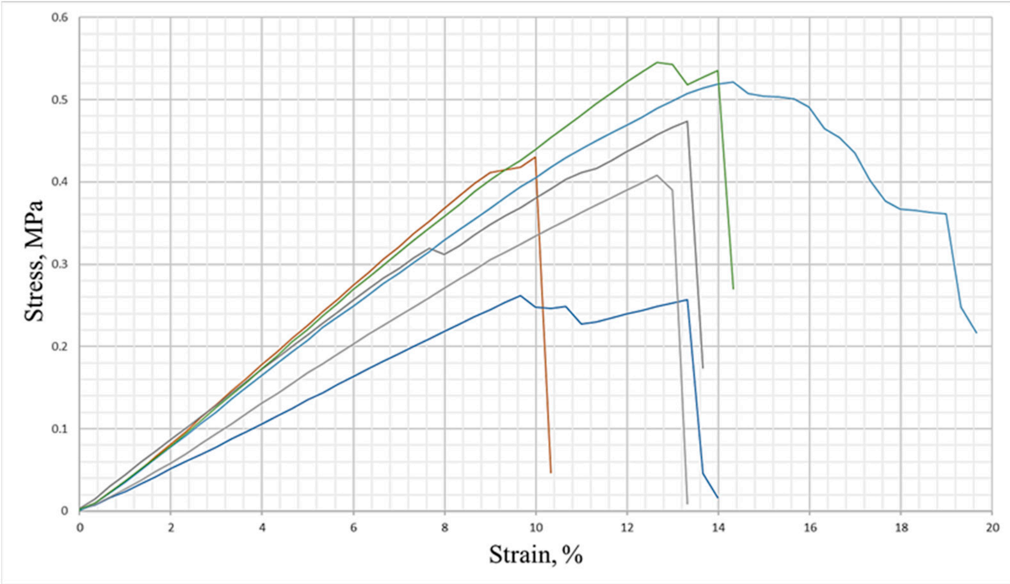


(**B**)



(**C**)

Figure 7. *Cont.*



(**D**)

Figure 7. Deformation at bending load of hybrid plywood (20 mm thickness): (**A**) panel type A; (**B**) panel type B; (**C**) panel type C; (**D**) panel type D. The different colours represent the deformation behaviour of the test samples.

The results of the performed *t*-test on a series of hybrid plywood showed that when comparing panel type A and panel type B, the *p*-value = 0.01289; comparing panel type B and panel type C, the *p*-value = 0.67827; and comparing panel type ***C*** and panel type D, the *p*-value = 0.31005. In general, only in the first case were the results statistically significant; thus, with a decrease in the number of peeler core sections in the core layer, the MOE values did not change significantly.

The results obtained for the MOR values showed a similar trend to the MOE (Figure 6).

The highest average MOR value of 17.9 N·mm^{-2} was determined for panel type ***A***. The average MOR values decreased by 23% (13.7 N·mm^{-2}) when the peeler core section ratio was 80% (panel type ***B***). When replacing UF with PF resin in the panels that had the same number of peeler core sections in the core layer (panel type ***B*** and panel type ***C***), a decrease in bending strength by 5% was observed (MOR = 13.0 N·mm^{-2}). This might be attributed to the lower spread rate of PF adhesive (170 g.m^{-2}), a more intensive absorption of the adhesive in the pores of the poplar wood and, last but not least, the secondary heat treatment. The face veneer sheets (1 and 2, and 4 and 5) were previously glued to create complete contact between them, and there were no gaps due to the lack of peeler core sections in the core layer. Additional heat treatment was subsequently performed to bond the peeler core sections to the double-face veneer sheets. In this case, although PF is resistant to thermal treatment, a partial thermal destruction of the adhesive seam may have occurred. Due to all the listed factors, there was a decrease in the strength characteristics of the hybrid plywood glued with PF. The MOR values of panel type D continued to decrease (MOR = 10.7 N·mm^{-2}). Despite the large number of gaps, the strength characteristics were significantly high considering the low density (304 kg·m^{-3}) of these panels.

A comparison between panel type A and panel type B regarding the determined MOR values was carried out using a *t*-test. The results showed that for this pairing, the *p*-value = 0.05313; comparing panel type B and panel type C, the *p*-value = 0.72862; and comparing panel type C and panel type D, the *p*-value = 0.09364. All comparative analyses indicated no statistical significance. These results can be explained by the reductions in the number of peeler core sections in the core layer, which decreased the bending strength.

The bending deformation behaviour of hybrid plywood with a thickness of 20 mm is presented in Figure 7.

When analysing the deformation behaviour and the load capacity of the different types of hybrid plywood with a thickness of 20 mm using the stress–strain relationships, it was found that the highest load capacity and limit stress was demonstrated by panel type A, or plywood with 100% filling bonded with UF adhesive. This type of plywood failed after an average stress of 0.7 MPa, and the deformation was about 20%. A slight drop in the maximum stress of approximately 16% was observed when the ratio of peeler core sections was reduced to 80%, in which case the maximum deformation before failure was about 15%. In the type C and type D panels, a subsequent drop in maximum stress to 0.5 MPa was observed, where the maximum strain before failure was maintained at about 15%.

Graphical representations of the mechanical characteristics (MOR and MOE) of the hybrid plywood panels manufactured with 30 mm thick poplar peeler core sections in the core layer are presented in Figures 8–10.

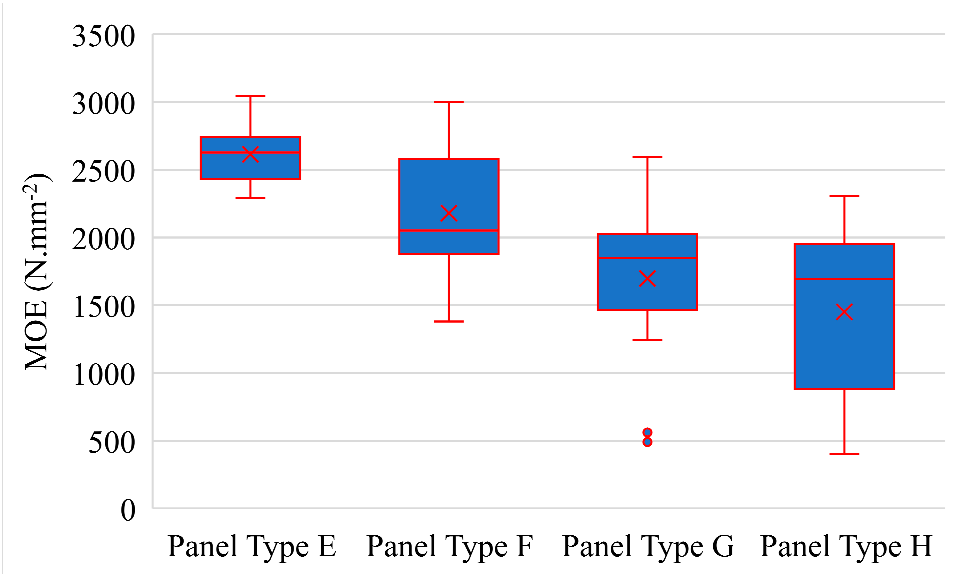


Figure 8. Modulus of elasticity (MOE) of hybrid plywood (30 mm thickness).

The trend in the MOE remained the same as that of hybrid plywood with a thickness of 20 mm (Figure 8).

The highest MOE values of 2613 N·mm^{-2} were observed for panel type E. The decreased number of peeler core sections in panel type F and panel type H resulted in lower MOE values of 2180 N·mm^{-2} and 1451 N·mm^{-2}, respectively.

The results of the conducted *t*-test on a series of hybrid plywood with a thickness of 30 mm displayed that when comparing panel type E and panel type F, the *p*-value = 0.13286; comparing panel type F and panel type G, the *p*-value = 0.41928; and comparing panel type F and panel type H, *p*-value = 0.41692. The results in all comparative analyses showed no statistical significance.

The determined average MOR values of the hybrid plywood fabricated with 30 mm thick poplar peeler core sections in the core layer are shown in Figure 9. Similar to the panels made with 20 mm thick peeler core sections, the reduced number of sections in the core layer resulted in lower MOR values.

The highest MOR value was determined for panel type E. It can be seen that the bending strength of the hybrid plywood with a thickness of 30 mm decreased almost double compared to the panels with a thickness of 20 mm (panel type A). This can be explained by the fact that in the face layers, there were only two veneer sheets of the same wood type and thickness, and in the core layer, the distance between the face layers was increased from 12 to 22 mm. Almost all test specimens were destroyed in the veneer area during testing, and only a few of them in the area of contact between the veneer and the peeler core sections. For this reason, the tensile forces in the lower part of the panels increased with an increase in the distance from the axis of symmetry. Therefore, the ultimate strength of the veneer of a given wood species was reached at a lower load (for panel type A, F_{max} = 613, and for panel type E, F_{max} = 527 N).

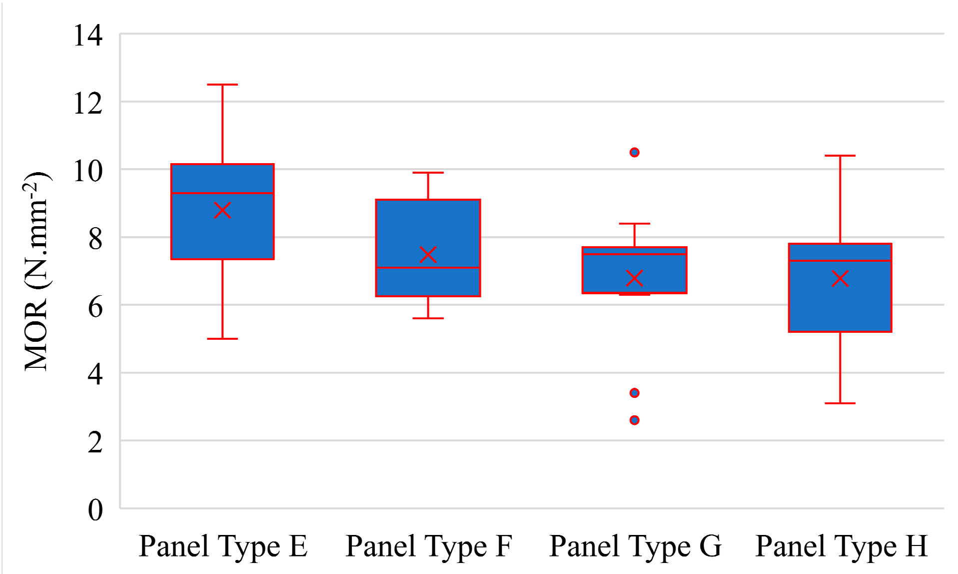


Figure 9. Bending strength (MOR) of hybrid plywood (30 mm thickness).

The determined MOR value for panel type F was 7.5 $N{\cdot}mm^{-2}$; a reduction of 15% in bending strength was noticed. The difference was slightly less significant compared to the hybrid plywood with a thickness of 20 mm. Changing UF to PF adhesive (panel type ***G***) with pre-bonding of the face veneer sheets again led to a slight decrease (9%), with an MOR = 6.8 $N{\cdot}mm^{-2}$. The average MOR value for panel type H, manufactured with the lowest number of peeler core sections in the core layers, was 6.8 $N{\cdot}mm^{-2}$.

The comparison between panel type E and panel type F regarding the determined MOR values was performed using a *t*-test. The results showed that the *p*-value = 0.13286; comparing panel type F and panel type G, the *p*-value = 0.41928; and comparing panel type F and panel type H, the *p*-value = 0.41692. The results in all comparative analyses exhibited no statistical significance.

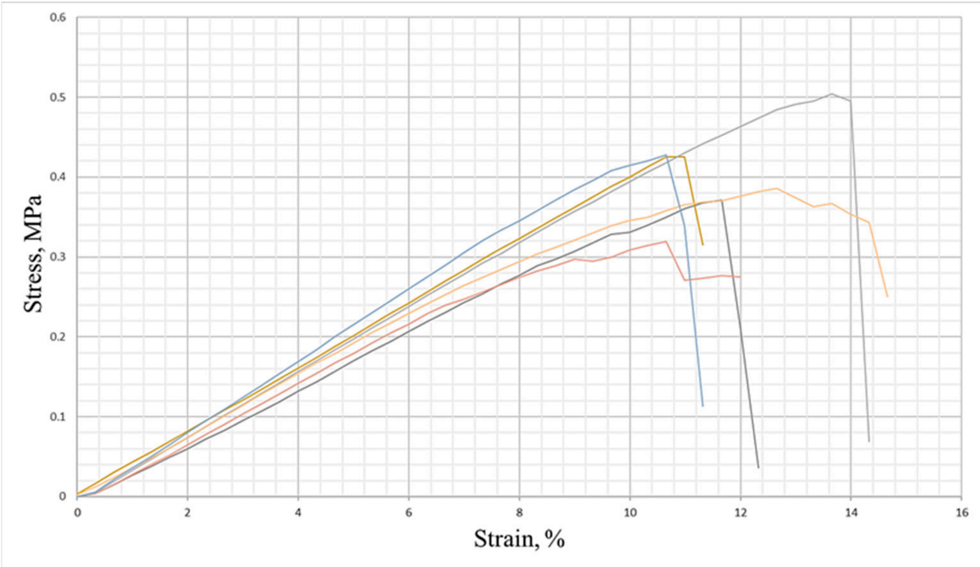
Figure 10 illustrates the bending deformation behaviour of hybrid plywood with a thickness of 30 mm.

When analysing the stress–strain relationships, it was found that the plywood bonded with the UF adhesive and the highest number of peeler core sections in the core layer (panel type I) had the highest stress resistance within the limits of 0.5 MPa for the hybrid plywood with a thickness of 28 mm. The maximum deformation before failure for this plywood was about 12%. The decreased number of peeler core sections in the core layer (panel type F) resulted in a 25% decrease in the tensile strength. A maximum deformation before failure of about 11% was observed in this type of plywood.

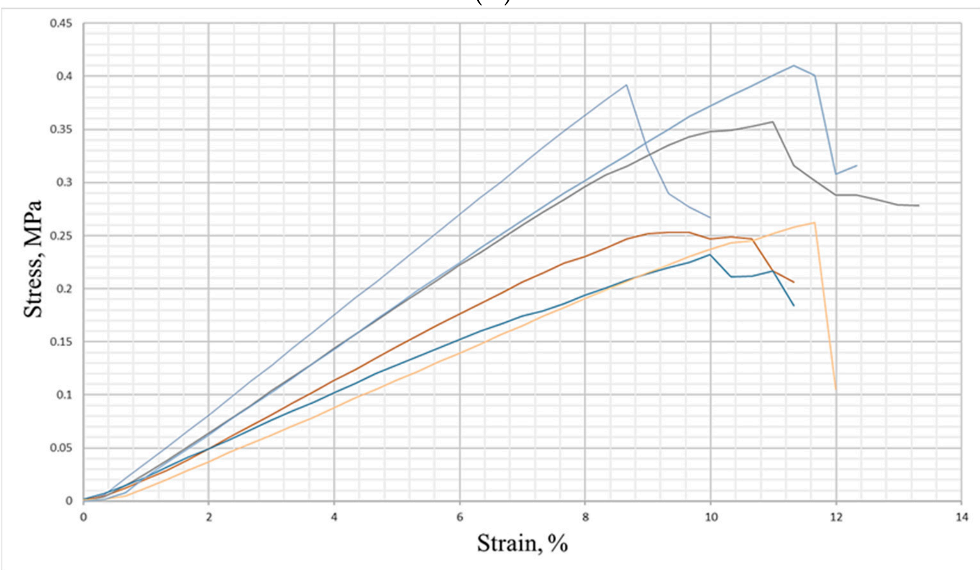
Panel type G and Panel type H exhibited similar stress resistances of about 0.35 MPa and a maximum deformation before failure of approximately 14%.

The last series of panels (panel type I, panel type J, and panel type K) of hybrid plywood were made to determine if replacing the poplar face veneers with hardwood species would affect the physical and mechanical properties of the panels.

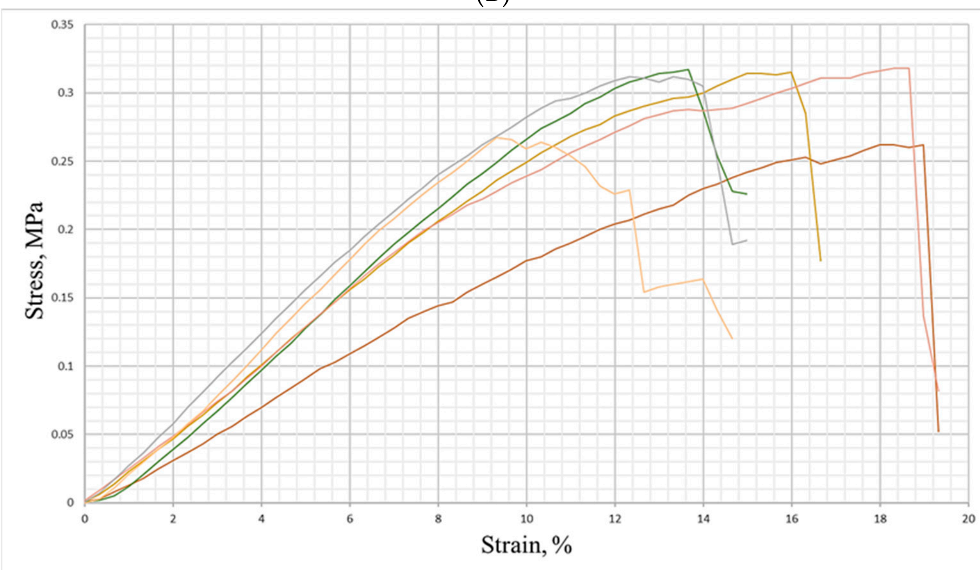
The obtained MOE results are shown in Figure 11.



(**A**)

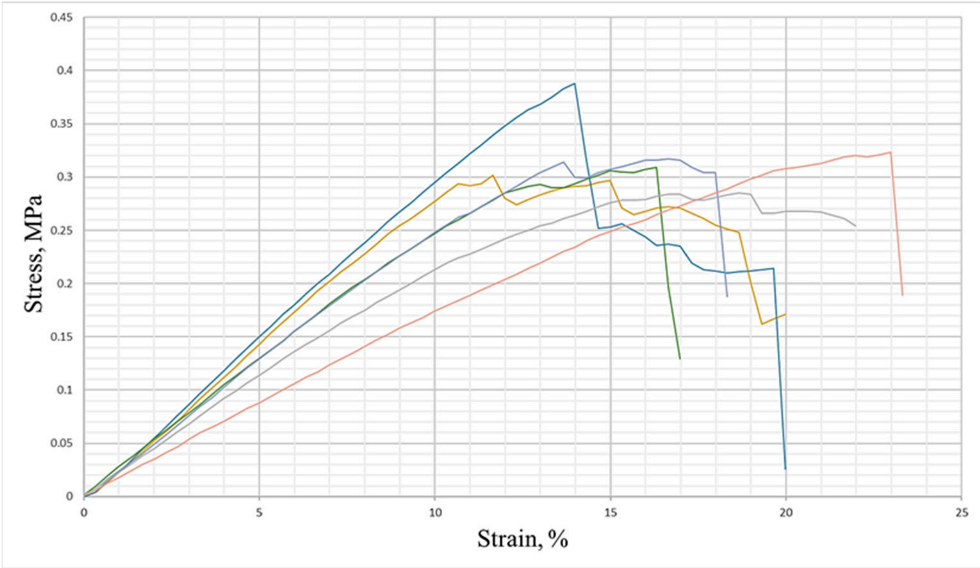


(**B**)



(**C**)

Figure 10. *Cont.*



(**D**)

Figure 10. Deformation at bending load of hybrid plywood (30 mm): (**A**) panel type E; (**B**) panel type F; (**C**) panel type G; (**D**) panel type H. The different colours represent the deformation behaviour of the test samples.

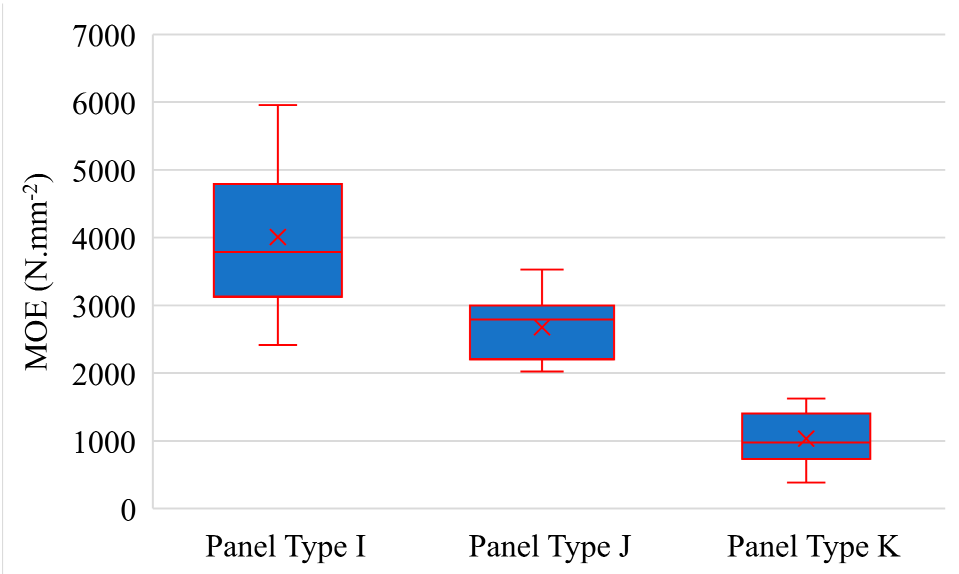


Figure 11. Modulus of elasticity (MOE) of hybrid plywood (18 and 28 mm thicknesses).

The average MOE values for hybrid plywood with a thickness of 18 mm (panel type I) were 4010 N·mm^{-2}. Compared to panel type B, manufactured with the same thickness and number of peeler core sections but from poplar wood, the MOE values increased by approximately 33%. The density of hybrid plywood when using beech veneer in the face layer increased by only 13%. In the second type of hybrid plywood (panel type J), with the increase in thickness to 28 mm and the maximum number of peeler core sections, the MOE reached 2677 N·mm^{-2}. Comparing it with the hybrid plywood with the same characteristics but with poplar veneer only (panel type E), the modulus of elasticity increased by 2% and the density by 6%, respectively. The MOE value obtained for panel type K was 1020 N·mm^{-2}. The modulus of elasticity decreased by 30% compared to panel type H. This can be explained by the lower number of peeler core sections and the secondary burning of the PF resin in the production of panel type K.

A graphical representation of the bending strength values of the hybrid plywood panels fabricated with beech veneers in the face layers is presented in Figure 12.

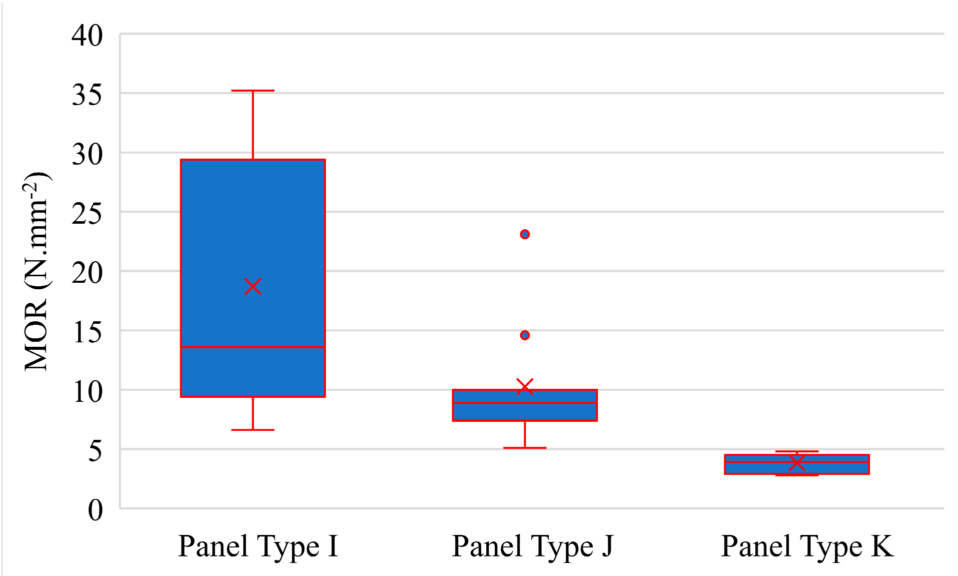


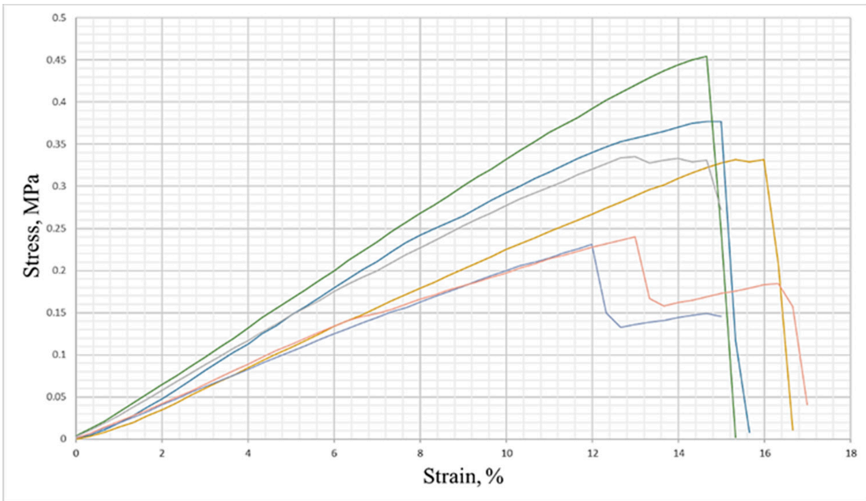
Figure 12. Bending strength (MOR) of hybrid plywood (18 and 28 mm).

The results of the bending strength investigation showed a trend similar to the other series of hybrid plywood with the same thickness but with poplar wood veneer only. In panel type I (MOR = 18.7 N·mm^{-2}), an increase of 27% was observed compared to panel type B, which had an MOR value of 10.3 N·mm^{-2}. Panel type J showed a 14% increase compared to panel type E. The determined MOR value of panel type K was 3.8 N·mm^{-2}.

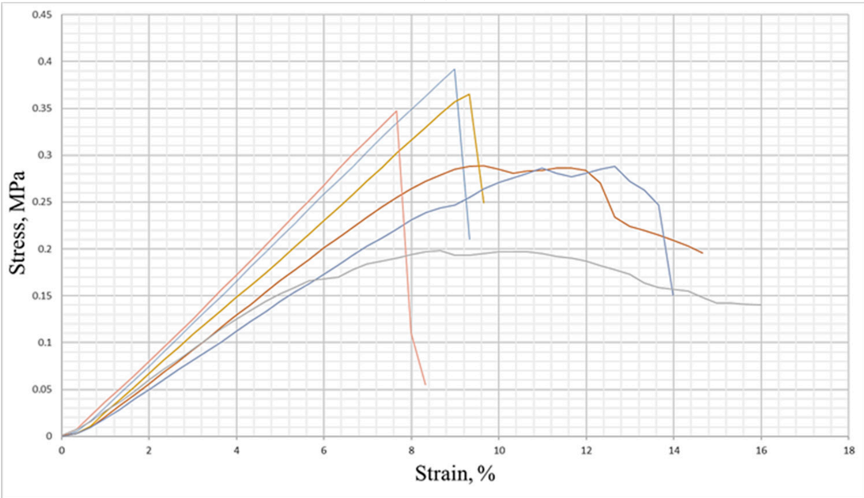
Based on the results obtained for the physical and mechanical properties of all tested hybrid panels, it can be concluded that peeler cores can be utilised as a raw material for producing hybrid plywood. The density-to-strength ratios of this lightweight plywood were also very promising [25]. Applying peeler cores as a filler in the core layer of hybrid lightweight plywood is rational and allows maximum utilisation. Another important fact is that the bonded hybrid plywood had excellent dimensional stability despite the small number of veneer sheets observed. This stability of the shape of the panels is a consequence of the orientation of the wood fibres of the washers. The larger number of washers provides significant assurance that when hardware or other fasteners are used, they will be securely clamped to the hybrid plywood. All this gives us a premise to claim that the manufactured hybrid plywood panels can be widely applied in the furniture industry as a construction material.

The deformation behaviour of hybrid plywood with a thickness of 18 and 28 mm is presented in Figure 13.

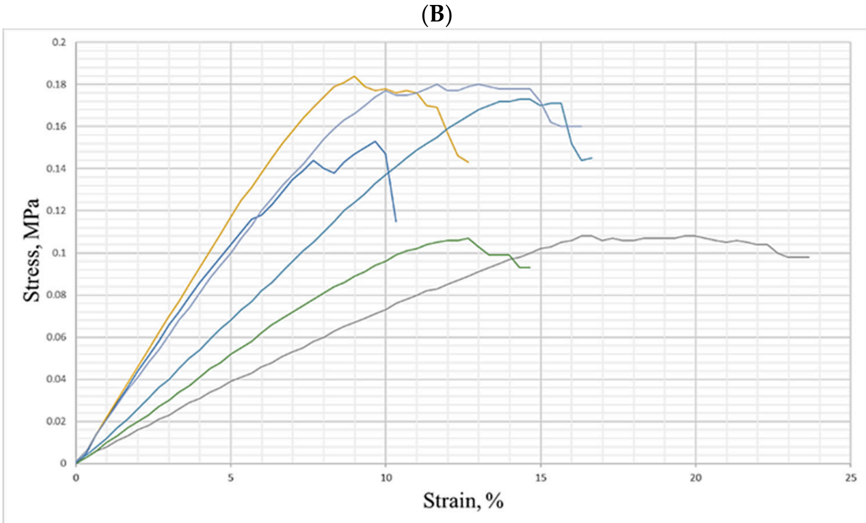
When analysing the deformation behaviour of the laboratory-produced hybrid plywood, it was found that the panels with a thickness of 18 mm manufactured from beech (panel type I and panel type G) exhibited an average resistance to tension within the limits of 0.4 MPa but with a significant variation in the values of this indicator (from 0.25 to 0.95 MPa). The deformation at failure of these types of plywood ranged from 10 to 16%, but some of the samples had a deformation of more than 30%. The ultimate tensile strength of panel type A dropped significantly to 0.15 MPa, at a deformation range from 10% to 20%. Further, even using the beech veneer, the negative tendency to decrease the load capacity (tensile resistance) with the increase in the thickness of the hybrid plywood was confirmed.



(**A**)



(**B**)



(**C**)

Figure 13. Deformation at bending load of hybrid plywood (18 and 28 mm): (**A**) panel type I; (**B**) panel type G; (**C**) panel type K. The different colours represent the deformation behaviour of the test samples.

4. Conclusions

The main novelty of this research work is the development of a new type of lightweight hybrid plywood panel produced by upcycling peeler cores, which are a by-product of plywood manufacturing. The proposed cutting method is maximally simplified, as the thickness of the panels mainly depends on the thickness of the peeler cores. Regardless of the number of peeler cores used in the core layer, hybrid plywood panels with very low density and excellent MOE and MOR values were produced. The best results were obtained for panel type *A* and panel type *I*, with the second type having a density increase of 13% compared to the first one. Replacing UF with PF adhesive did not improve the mechanical properties of the hybrid plywood. This might be attributed to the increased permeability of the adhesive in poplar wood, the lower consumption of PF resin compared to UF adhesive, and the secondary burning of the resin, which led to partial destruction of the adhesive joints. The findings of this study provide evidence suggesting that by-products from the plywood industry can be efficiently utilised in the development of a high-value-added product with a wide range of commercial applications. Future studies in the field should be focused on optimising the hot-pressing parameters and treatment of the edges of the hybrid plywood panels in order to achieve optimal performance.

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References

1. Reinprecht, L.; Iždinský, J. Composites from recycled and modified woods—Technology, properties, application. *Forests* **2021**, *13*, 6. [CrossRef]
2. Food and Agriculture Organisation of the United Nations: FAO. *Classification of Forest Products*; FAO: Rome, Italy, 2024. [CrossRef]
3. Dukarska, D.; Kawalerczyk, J.; Kmieciak, J. Modified pine needles as a formaldehyde scavenger for urea-formaldehyde resin in plywood production. *Eur. J. Wood Wood Prod.* **2024**, *82*, 147–158. [CrossRef]
4. Petrova, B.; Jivkov, V.; Yavorov, N. Possibilities for efficient furniture construction made of thin and ultra-thin materials by using mitre joints. *Materials* **2023**, *16*, 6855. [CrossRef] [PubMed]
5. Jivkov, V.; Simeonova, R.; Kamenov, P.; Marinova, A. Strength properties of new lightweight panels for furniture and interior. In Proceedings of the 23rd International Scientific Conference "Wood is Good—With Knowledge and Technology to a Competitive Forestry and Wood Technology Sector", Zagreb, Croatia, 12 October 2012; pp. 49–58.
6. Castro, G.; Fragnelli, G. New technologies and alternative uses for poplar wood. *Bol. Inf. CIDEU* **2006**, *2*, 27–36. Available online: https://dialnet.unirioja.es/servlet/articulo?codigo=2258287 (accessed on 11 February 2024).
7. Balatinecz, J.J.; Kretschmann, D.E. Properties and utilisation of poplar wood. In *Poplar Culture in North America*; Part A, Chapter 9; Dickmann, D.I., Isebrands, J.G., Eckenwalder, J.E., Richardson, J., Eds.; NRC Research Press, National Research Council of Canada: Ottawa, ON, Canada, 2001; pp. 277–291. Available online: https://www.fs.usda.gov/treesearch/pubs/8597 (accessed on 4 February 2024).
8. Sinković, T.; Jambreković, B.; Šefc, B.; Ištok, I.; Veseličić, F.; Sedlar, T. Some physical and mechanical properties of white poplar (*Populus alba* L.) wood grown in Varaždin region. In Proceedings of the 28th International Conference on Wood Science and Technology, Zagreb, Croatia, 7–8 December 2017; pp. 101–106. Available online: https://www.bib.irb.hr/914647 (accessed on 20 March 2024).

9. Syafii, S.; Novari, F. Study of veneer yield and amount of waste in veneer stripping with spindle-less type rotary lathe machine. *Bul. Poltanesa* **2021**, *22*, 95–100. [CrossRef]
10. Fonseca, M.A. *The Measurement of Roundwood: Methodologies and Conversion Ratios*; CABI Publishing: Cambridge, UK, 2005; pp. 107–116.
11. Melo, R.; Del Menezzi, C.H.S.; Pavan, B.E.; Rodolfo Júnior, F. Rotary peeling yield of *Schizolobium amazonicum* (*Leguminosae—Caesalpinioideae*). *Acta Amaz.* **2014**, *44*, 315–320. [CrossRef]
12. Koynov, D.; Grigorov, R.; Valyova, M. A novel method for producing a glulam from the wood of peeler cores. *Maderas Cienc. Tecnol.* **2022**, *24*, 1–14. [CrossRef]
13. Koynov, D.; Valyova, M. Utilisation of peeler cores for producing beams with hollow cross-section. *Drewno* **2022**, *65*. [CrossRef]
14. *EN 317:1998*; Particleboards and Fibreboards—Determination of Swelling in Thickness after Immersion in Water. European Committee for Standardization: Brussels, Belgium, 1998.
15. *EN 323:2001*; Wood-Based Panels—Determination of Density. European Committee for Standardization: Brussels, Belgium, 2001.
16. *ISO 13061-2:2014*; Physical and Mechanical Properties of Wood—Test Methods for Small Clear Wood Specimens—Part 2: Determination of Density for Physical and Mechanical Tests. International Organization for Standardization: Geneva, Switzerland, 2014.
17. *EN 310:1999*; Wood-Based Panels—Determination of Modulus of Elasticity in Bending and of Bending Strength. European Committee for Standardization: Brussels, Belgium, 1999.
18. Jivkov, V.; Petrova, B. Comparative analysis of physical and mechanical properties of some thin and ultra-thin wood-based and non-wood-based furniture panels. In Proceedings of the 11th International Scientific and Technical Conference "Innovations in forest industry and engineering design", Samokov, Bulgaria, 3–5 October 2022; pp. 83–98.
19. Omer, S.E.; Ćehić, M.; Hodžić, A. Analysis of properties of plywood for some areas of usage in wooden constructions. In Proceedings of the 11th International Research/Expert Conference "Trends in the Development of Machinery and Associated Technology", Hammamet, Tunisia, 5–9 September 2007.
20. Lovrić, A.; Zdravković, V.; Popadić, R.; Milić, G. Properties of plywood boards composed of thermally modified and non-modified poplar veneer. *BioResources* **2017**, *12*, 8581–8594. [CrossRef]
21. Bal, C.B.; Bektaş, İ. Some mechanical properties of plywood produced from eucalyptus, beech, and poplar veneer. *Maderas Cienc. Tecnol.* **2014**, *16*, 99–108. [CrossRef]
22. Bal, C.B.; Bektas, I.; Mengeloğlu, F.; Karakus, K.; Demir, H.Ö. Some technological properties of poplar plywood panels reinforced with glass fiber fabric. *Constr. Build. Mater.* **2015**, *101*, 952–957. [CrossRef]
23. De Boever, L.; Vansteenkiste, D.; Van Acker, J.; Stevens, M. End-use related physical and mechanical properties of selected fast-growing poplar hybrids (*Populus trichocarpa* × *P. deltoides*). *Ann. For. Sci.* **2007**, *64*, 621–630. [CrossRef]
24. *EN 622-5:2010*; Fibreboards—Specifications—Part 5: Requirements for Dry Process Boards (MDF). European Committee for Standardization: Brussels, Belgium, 2010.
25. Fekiač, J.; Gáborík, J.; Vojtkuliak, M. Properties of plywood made from perforated veneers. *Forests* **2021**, *12*, 1709. [CrossRef]