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Properties of Plywood Panels Composed of Thermally Densified and Non-Densified Alder and Birch Veneers

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Abstract: Ukrainian companies mainly use birch in the manufacture of plywood, but species, such as black alder, are not yet widely used in the manufacture of plywood due to their poorer properties. It is well known that thermal compression is often used to improve the properties of solid wood. Good lay-up schemes of veneer can maximize the advantages and minimize the disadvantages of these wood species, and generally improve the utility value of the plywood. This research aimed to develop plywood panels with two wood species and two types of veneer treatments in order to evaluate the influences of different lay-up schemes on the properties of the plywood. Five-layer plywood panels were formed with 16 different lay-up schemes using birch (*Betula verrucosa* Ehrh.) (B) and black alder (*Alnus glutinosa* L.) (A) veneers, which were non-densified (N) and thermally densified (D). The different lay-up schemes were used to identify opportunities to improve the mechanical and physical properties of the plywood by replacing the birch veneer in the plywood structure with an alternative alder veneer. The veneer sheets were thermally densified in a laboratory hot press at a temperature of 180 °C and pressure of 2 MPa for 3 min. The conducted study showed that the bending strength, modulus of elasticity and shear strength of mixed-species plywood (B^D–A^N–A^N–A^N–B^D) increased by up to 31.5%, 34.4% and 16.8%, respectively, in comparison to those properties of alder plywood from non-densified veneer (A^N–A^N–A^N–A^N–A^N), by positioning alder non-densified veneers in the core layers and birch densified veneers in the outer layers. Moreover, the surface roughness of plywood panels with outer layers of birch veneer was lower than that of panels with outer layers of alder veneer. It was shown that non-treated alder veneer, despite exhibiting somewhat lower strength properties than birch veneer, could be successfully used with proper lay-up schemes in the veneer-based products industry.

Keywords: birch; black alder; thermal densification; plywood properties; wood veneers

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1. Introduction

Nowadays, veneer-based products, including plywood and laminated veneer lumber (LVL), are highly effective engineering wood products for construction. The plywood manufacturing process creates products with several dimensions to suit architectural and structural purposes, and mechanical properties equivalent or superior to those of the initially solid wood [1]. However, various process variables should be considered to obtain panels with satisfactory properties, such as the wood species used, type of adhesive, density, moisture content, lay-up scheme of the veneers, etc. [2]. The choice of wood species is very important for the properties and price of the panel [3]. Ukrainian companies mainly use birch (*Betula verrucosa* Ehrh.) in the manufacture of plywood, but species such as black alder (*Alnus glutinosa* L.) are not yet widely used in the manufacture of plywood due to their poorer mechanical properties. However, mixing veneers from different species can be a good strategy for obtaining panels with a good cost–benefit relationship [4].

Various modification methods can be used to improve the properties of low-grade wood species, one of which is the thermal densification of wood at elevated temperatures and pressure [5]. The combination of heat and compression is an environmentally friendly modification method that does not require any chemicals. Previous studies have shown that thermal densification not only improves the aesthetic properties and reduces surface roughness, but also improves the mechanical properties and bonding quality [6–11]. Moreover, the thermal densification of the veneer used for the manufacture of plywood or lamination of wood-based panels reduces the consumption of adhesive and pressing pressure by 40%, the consumption of lacquer materials and the bonding strength improves [12,13].

Various studies on veneer-based products indicated that the lay-up scheme is a key factor in improving the mechanical properties of products and beneficial use of available low-grade and lower cost wood species [14–24]. LVL panels, made by combining veneers from durable and non-durable wood species, showed improved durability when two faces and one core veneer were from decay-resistant species [14]. In other studies, it was shown that the most suitable lay-up schemes for poplar and beech veneers [15] or poplar and birch veneers [17] were eight- and ten-ply LVL, respectively, with high bending properties. Several authors [18,20] studied the effect of the thermal modification process on the properties of plywood panels manufactured by combining thermally treated and untreated poplar veneers. It was found that the addition of thermally treated veneers caused a decrease in the mechanical properties and improved the dimensional stability of plywood panels. On the contrary, other results revealed that the mechanical properties of plywood composed of fully and partially heat-treated veneers were not significantly different from those of untreated plywood [24].

One of the lay-up schemes (construction strategy) of veneers is to place the high-density wood veneers in the outer layers and low-density veneers in the inner layers of veneer-based panels [19,25]. H'ng et al. [25] manufactured 11-ply and 15-ply LVL panels by combining high-density keruing veneers (as outside veneers) with low-density wood veneers such as pulai, sesendok and kekabu hutan. They found that combining the keruing (as surface layers) and low-density wood veneers gave a greater bending strength and more stable material.

Another lay-up strategy is to combine softwood and hardwood veneers to manufacture mixed-species veneer-based products [21,22,26]. Combining even a small amount of spotted gum veneer with plantation hoop pine veneer resulted in an improved mechanical performance, especially in flatwise bending [22]. These authors showed that the substitution of only two spotted gum veneers on the faces of the hoop pine 12-ply LVL panels yielded an increase of up to 34.5% (MOE) and 38.5% (MOR) compared with the all hoop pine 12-ply LVL panels. Another study [19] on manufacturing 7-ply LVL panels using five different lay-up strategies that combined ash and Turkish red pine veneers showed that the best results in terms of the density, MOR and MOE were achieved in the panels with outer layers comprising ash veneers. Ozarska [4], when comparing softwoods with hardwoods, noted that the softwoods were more susceptible to bonding, but the hardwoods provides increased strength and structural rigidity to the finished product.

In our previous work [27], we presented the possibility of creating plywood panels with different strength properties when combining beech veneers of different thicknesses, as well as thermally densified and non-densified veneers. It was found that the use of densified veneers increased the mechanical properties of plywood but worsened the thickness of swelling and water absorption of panels.

However, there is no information in the literature about the manufacture of plywood panels by combining thermally densified and non-densified veneers of different high-grade and low-grade hardwood species in one plywood panel. It is hypothesized that mixing veneers from high- and low-grade wood species may improve the properties of the resulting mixed-species plywood panels by maximizing the advantages and overcoming the disadvantages of the two resources. Therefore, the aim of this work was to evaluate the effect of combining different high-grade (birch, which has relatively better structural properties) and low-grade (black alder, with poorer properties but a lower cost) wood species and different lay-up schemes on the mixed-species plywood properties made from alternate layers of densified and non-densified veneers.

2. Materials and Methods

2.1. Materials

Commercially produced rotary-cut veneers of birch (*Betula verrucosa* Ehrh.) and black alder (*Alnus glutinosa* L.) were used in the study. Birch wood is commonly used to manufacture veneer and plywood in Ukraine. Alder wood was chosen based on its economic advantages because it is a cheap species and is commonly used for the manufacture of plywood in Ukraine, as a substitution for traditionally used birch wood. Birch and alder veneers had an equal thickness of 1.6 mm, moisture content of 5.7% and 7.0%, respectively, and a density of 677 kg/m^3 and 487 kg/m^3, respectively. A total of 240 veneer samples with a dimension of 300 × 300 mm were prepared for the production of plywood.

Commercial urea-formaldehyde (UF) resin (density = 1.28 g/m^3, solids content = 65 ± 2%, pH = 7.5 ± 0.5, viscosity 1000–2500 mPa·s at 20 °C), kaolin (as a filler), ammonium nitrate NH_4NO_3 (as a hardener) and distilled water were used to prepare the adhesive. For the preparation of UF adhesive, 5% hardener and 2% filler were used.

2.2. Thermal Compression of Veneer

Veneer samples without visible defects were selected for thermal compression. The veneer sheets were densified between smooth metal sheets, which were placed on the hot press. Each veneer sheet was densified at a temperature of 180 °C, pressure of 2 MPa and for a duration of 3 min (during the last minute of compression, the pressure was gradually released).

The changes of the densified veneer properties were evaluated using veneer thickness and density measurements. To achieve this, the weight and dimensions of the veneer specimens were measured before and after thermal compression. Based on these data, the compression ratio (*CR*) and densification ratio (*DR*) of the veneer sheets after the thermal compression process were calculated as follows:

$$CR = (T_n - T_d)/T_n \times 100 \quad (1)$$

where T_n is the thickness of the veneer before compression (mm) and T_d is the thickness of the veneer after compression (mm).

$$DR = (D_d - D_n)/D_n \times 100 \quad (2)$$

where D_n is the density of the veneer before compression (kg/m^3) and D_d is the density of the veneer after compression (kg/m^3).

2.3. Manufacturing and Testing of Plywood Samples

Five-layer plywood panels with dimensions of 300 × 300 mm were manufactured. The veneer assembly for the production of plywood samples was formed from either birch or black alder veneers only, or from birch veneer combined with black alder veneer, with non-densified and densified veneers in one package. There was a total of 16 different veneer panel set options (Table 1). The adhesive spread was 110 g/m^2 and adhesive was applied by hand to one side of each veneer using a roller. Conditions for pressing plywood samples were as follows: temperature 130 °C, pressure 1.8 MPa, time 5.5 min (during the last minute, the pressure was smoothly released).

Table 1. Configuration of five-layer plywood panels.

Code of Panels	Type of Panels	Veneer Assembly Pattern by Wood Species	Veneer Assembly Pattern by Type of Veneer Treatment
I	B^N–B^N–B^N–B^N–B^N	B–B–B–B–B	N–N–N–N–N
II	B^N–A^N–B^N–A^N–B^N	B–A–B–A–B	N–N–N–N–N
III	B^N–A^N–A^N–A^N–B^N	B–A–A–A–B	N–N–N–N–N
IV	A^N–B^N–B^N–B^N–A^N	A–B–B–B–A	N–N–N–N–N
V	A^N–B^N–A^N–B^N–A^N	A–B–A–B–A	N–N–N–N–N
VI	A^N–A^N–A^N–A^N–A^N	A–A–A–A–A	N–N–N–N–N
VII	B^D–A^N–A^N–A^N–B^D	B–A–A–A–B	D–N–N–N–D
VIII	A^D–B^N–B^N–B^N–A^D	A–B–B–B–A	D–N–N–N–D
IX	B^D–A^N–B^D–A^N–B^D	B–A–B–A–B	D–N–D–N–D
X	A^D–B^N–A^D–B^N–A^D	A–B–A–B–A	D–N–D–N–D
XI	B^D–B^D–B^D–B^D–B^D	B–B–B–B–B	D–D–D–D–D
XII	B^D–A^D–B^D–A^D–B^D	B–A–B–A–B	D–D–D–D–D
XIII	B^D–A^D–A^D–A^D–B^D	B–A–A–A–B	D–D–D–D–D
XIV	A^D–B^D–B^D–B^D–A^D	A–B–B–B–A	D–D–D–D–D
XV	A^D–B^D–A^D–B^D–A^D	A–B–A–B–A	D–D–D–D–D
XVI	A^D–A^D–A^D–A^D–A^D	A–A–A–A–A	D–D–D–D–D

B—birch veneer; A—alder veneer; N—non-densified veneer; D—densified veneer.

After pressing, the plywood panels were conditioned for one week in an environmental chamber maintained at 65 ± 5% relative humidity and 20 ± 2 °C before their properties were evaluated. For each variant in the experimental plan (Table 1), three panels were made, that is, there was a total of 48 panels. After conditioning, samples were cut from the manufactured panels into required test sizes according to relevant standards. In accordance with European standards, the following number of samples was evaluated for each panel variant: three samples for moisture content (EN 322) [28], ten samples for density (EN 323) [29], three samples for bending strength (MOR) (EN 310) [30] and modulus of elasticity (MOE) (EN 310) [30], ten samples for shear strength (EN 314) [31,32] and ten samples for thickness swelling (*TS*) (EN 317) [33] and water absorption (*WA*). The samples for shear strength testing were immersed in water at 20 ± 3 °C for 24 h for plywood bonding class 1 (dry conditions).

The samples for *TS* and *WA* testing were immersed in distilled water for 24 h. After this time, the test pieces were removed from the water, weighed, and the thickness was measured. The percent change from the original thickness represents the *TS*, and the percent weight change from the original weight represents the *WA*. The *WA* and *TS* of plywood panels samples were calculated according to the following formulae:

$$WA = (W_2 - W_1)/W_1 \times 100 \quad (3)$$

$$TS = (T_2 - T_1)/T_1 \times 100 \quad (4)$$

where W_1 and T_1 are the initial weight (g) and thickness (mm) before soaking, and W_2 and T_2 are the final weight (g) and thickness (mm) after soaking.

Surface roughness of plywood panels was measured using a digital microscope VHX-5000 (Keyence, Itasca, IL, USA) with a VH-Z100R wide depth of field objective. 3D images of the surface were taken, from which the overall profile and height parameters of the surface were measured. Three surface roughness characteristics were determined, i.e., the arithmetic average height (R_a), average peak to valley roughness (R_z) and root-mean-square deviation of the profile (R_q). The measurement was performed for two samples from the measured group (two random repetitions on each sample) in the transverse direction. The resulting values were reported as mean values per group.

Samples (5 × 5 mm) were cut from the panel to analyze microscopic structure of bond line and effect of veneer densification on adhesive penetration of plywood panels using an electron microscope (MIRA3 LMU, Tescan, a. s., Brno, Czech Republic). The bond line was softened with water and then immediately cleaned up with a razor blade. An accelerating voltage of 7 keV and a beam current of approximately 30 pA were used for result visualizations.

2.4. Statistical Analysis

The effects of combining veneers of different wood species and different types of veneer treatment on the properties of the laboratory-fabricated plywood panels were analyzed using analysis of variance (ANOVA), with a 0.05 level of significance using statistical software program STATISTICA 12.0 package (StatSoft Inc., Tulsa, OK, USA). Duncan's range tests were conducted to determine significant differences between mean values.

3. Results and Discussion

3.1. Compression and Densification Ratio of Veneers

The average values of the physical characteristics of thermally densified veneers are given in Table 2. During thermal compression, some changes in the physical properties of the thermally densified veneers could be observed. Thermal compression reduced the thickness of the veneer, and, therefore, the volume, which increased the density. In particular, the density of alder and birch veneers increased after the thermal compression to 528 and 708 kg/m^3, respectively. This result was in agreement with those reported by other researchers [34], who found that veneer density increased by 14% under thermal compression at a pressure of 2.7 MPa and temperature of 180 °C for 2 min. Considering the lower density of the alder veneer compared to the birch veneer, it is natural that the *CR* and *DR* of the alder veneer were higher (11.5% and 8.3%, respectively) than similar indicators for the birch veneer (8.2% and 4.6%, respectively). The values of *CR* were higher than the values of *DR*. This difference was explained by the fact that the *CR* takes into account changes in the thickness of the veneer only, and the *DR* takes into account both changes in the thickness and mass of the veneer. The mass of the veneer also decreased in the process of thermal compression. The decrease in mass could be explained by the loss (evaporation) of moisture under the influence of pressure and temperature [12]. In previous studies [35], no chemical changes were observed in thermally densified wood veneers in the case of a similar modification. Similar results were also reported by Rautkari et al. [36], who, using FTIR spectroscopic analysis, showed that no significant chemical changes occurred during frictional compression. The difference between the absolute values of *CR* and *DR* was 3.2% and 3.6%, respectively, for the alder and birch veneers. This was explained by the slightly higher moisture content of the alder veneer (7.0%) than the birch veneer (5.7%). It should also be noted that during thermal compression of the veneer the surface roughness of the veneer decreased and its aesthetic properties improved [8–10].

Table 2. The mean values of physical properties of thermally densified veneers.

Wood Species	Density of Veneer (kg/m^3)		Compression Ratio (%)	Densification Ratio (%)
	Non-Densified	Densified		
Alder	487 (21)	528 (20)	11.5 (2.3)	8.3 (1.9)
Birch	677 (41)	708 (51)	8.2 (1.4)	4.6 (0.8)

Values in parentheses are standard deviations.

3.2. Thickness and Density of Plywood Samples

The physical properties of plywood samples, which were made by combining veneers of different wood species and different types of treatment in one panel, are summarized in Table 3. The thinnest and thickest plywood samples were 6.7 mm and 7.4 mm and were made of only densified alder veneer (A^D–A^D–A^D–A^D–A^D) and only non-densified birch veneer (B^N–B^N–B^N–B^N–B^N), respectively. Between all other samples, the thickness of the panels differed insignificantly and was in the range of 6.9–7.2 mm. The thickness of the plywood panels in this study did not exceed the tolerances for unsanded panels according to European standard EN 315 [37]. The lowest density of 583 kg/m^3 was found in plywood (A^N–A^N–A^N–A^N–A^N) from non-densified alder veneer, as expected. The greatest densities of 779 and 832 kg/m^3 were found in plywood made of non-densified birch veneer (B^N–B^N–B^N–B^N–B^N) and densified birch veneer (B^D–B^D–B^D–B^D–B^D), respectively. The lowest *WA* values of 29.3% and 30.4% were found in plywood samples made of densified (B^D–B^D–B^D–B^D–B^D) and non-densified birch veneer (B^N–B^N–B^N–B^N–B^N), respectively. The highest *WA* values of 41.9% and 43.0% were found in plywood samples made of densified (A^D–A^D–A^D–A^D–A^D) and non-densified (A^N–A^N–A^N–A^N–A^N) alder veneer, respectively. The smallest and greatest values of *TS* of 7.2% and 12.1% were observed in plywood made from non-densified (A^N–A^N–A^N–A^N–A^N) and densified (A^D–A^D–A^D–A^D–A^D) alder veneer, respectively.

Table 3. Values of physical properties of plywood samples.

Code of Panel	Type of Panel	Thickness (mm)	Density (kg/m^3)	*WA* (%)	*TS* (%)
I	B^N–B^N–B^N–B^N–B^N	7.4 ^{g} (0.1)	779 ^{h} (31)	30.4 ^{a} (2.4)	7.9 ^{abc} (0.9)
II	B^N–A^N–B^N–A^N–B^N	7.2 ^{def} (0.2)	685 ^{cde} (24)	36.3 ^{c} (2.0)	9.4 ^{cdef} (1.7)
III	B^N–A^N–A^N–A^N–B^N	7.2 ^{ef} (0.2)	684 ^{cde} (20)	36.3 ^{c} (2.2)	8.0 ^{abc} (1.3)
IV	A^N–B^N–B^N–B^N–A^N	7.0 ^{bcdef} (0.3)	709 ^{ef} (27)	33.2 ^{b} (2.7)	8.5 ^{abcd} (1.4)
V	A^N–B^N–A^N–B^N–A^N	7.0 ^{bcdef} (0.3)	661 ^{bc} (27)	35.6 ^{bc} (1.3)	7.6 ^{ab} (2.2)
VI	A^N–A^N–A^N–A^N–A^N	7.2 ^{cdef} (0.1)	583 ^{a} (18)	43.0 ^{e} (3.9)	7.2 ^{a} (1.3)
VII	B^D–A^N–A^N–A^N–B^D	7.1 ^{cdef} (0.1)	673 ^{cd} (15)	39.0 ^{d} (2.5)	9.0 ^{bcde} (1.1)
VIII	A^D–B^N–B^N–B^N–A^D	7.1 ^{bcdef} (0.1)	726 ^{fg} (52)	36.2 ^{c} (2.8)	10.3 ^{ef} (1.4)
IX	B^D–A^N–B^D–A^N–B^D	7.1 ^{bcdef} (0.3)	712 ^{ef} (18)	35.0 ^{bc} (1.4)	10.0 ^{def} (1.9)
X	A^D–B^N–A^D–B^N–A^D	7.0 ^{bc} (0.1)	703 ^{ef} (29)	35.3 ^{bc} (2.2)	9.3 ^{cdef} (1.0)
XI	B^D–B^D–B^D–B^D–B^D	7.2 ^{fg} (0.2)	832 ^{i} (44)	29.3 ^{a} (1.4)	10.9 ^{fg} (2.3)
XII	B^D–A^D–B^D–A^D–B^D	7.0 ^{bcd} (0.3)	744 ^{g} (47)	35.5 ^{bc} (1.9)	10.9 ^{fg} (1.5)
XIII	B^D–A^D–A^D–A^D–B^D	7.0 ^{bcde} (0.1)	675 ^{cd} (6)	37.3 ^{cd} (3.3)	10.3 ^{ef} (1.0)
XIV	A^D–B^D–B^D–B^D–A^D	6.9 ^{b} (0.1)	708 ^{ef} (14)	34.6 ^{bc} (2.2)	10.1 ^{ef} (1.5)
XV	A^D–B^D–A^D–B^D–A^D	7.0 ^{bcd} (0.1)	695 ^{de} (18)	37.3 ^{cd} (2.5)	10.9 ^{fg} (2.1)
XVI	A^D–A^D–A^D–A^D–A^D	6.7 ^{a} (0.2)	638 ^{b} (24)	41.9 ^{e} (4.6)	12.1 ^{g} (1.9)

Values in parentheses are standard deviations; means followed by the same letter were not significantly different at $p \leq 0.05$.

The ANOVA analysis (Table 4) showed that combinations of wood species and having different types of veneer treatment in one panel significantly affected the thickness, density and *WA* of plywood samples. In addition, the combination of a densified and non-densified veneer in one panel affected the thickness and density of plywood samples to almost the same extent, taking into account approximately the same influencing factors (F = 10.355 and F = 13.334). Meanwhile, the combination of veneers of different wood species in one panel had a stronger effect on the density (F = 101.404) and a weaker effect on the thickness (F = 9.464) of plywood samples. *TS* did not depend on the mixing of wood species (F = 1.527) in one panel, but significantly depended on the mixing of densified and non-densified veneers (F = 31.045) (Table 4).

Table 4. The influence of the variable factors on the physical properties of plywood.

Source of Variation	Thickness		Density		*WA*		*TS*	
	F	Sig.	*F*	Sig.	*F*	Sig.	*F*	Sig.
W	9.464	0.000	101.404	0.000	51.493	0.000	1.527	0.185
T	10.355	0.000	13.334	0.000	4.148	0.007	31.045	0.000
W × T	1.837	0.084	4.625	0.000	0.966	0.458	2.526	0.018

W—combination of veneers of different wood species; T—combination of veneers with different treatment.

A graphic illustration of the effect of combining veneers of different wood species and different treatments in one panel on the thickness, density, *WA* and *TS* of plywood panels is presented in Figure 1. The smallest average thickness (6.7 mm) was in plywood samples made from a densified alder veneer, and the largest (7.4 mm) was in samples made from a non-densified birch veneer (Table 3, Figure 1). Decreasing the share of alder veneer in the panel increased the thickness of the plywood samples, although this increase was insignificant. For the lower proportion (40%) of alder veneer in one panel, the thickness of samples with outer layers of non-densified (A^N–B^N–B^N–B^N–A^N) or densified (A^D–B^D–B^D–B^D–A^D) alder veneer was lower (7.0 mm and 6.9 mm, respectively) than the thickness of samples with outer layers of non-densified (B^N–A^N–B^N–A^N–B^N) or densified (B^D–A^D–B^D–A^D–B^D) birch veneer (7.2 mm and 7.0 mm, respectively); however, the difference between them was insignificant ($p > 0.05$). For the higher proportion (60%) of alder veneer in one panel, the thickness of samples (A^N–B^N–A^N–B^N–A^N) with outer layers of non-densified alder veneer was lower (7.0 mm) than the thickness of samples (B^N–A^N–A^N–A^N–B^N) with outer layers of non-densified birch veneer (7.2 mm). For the same conditions, the thickness of samples (A^D–B^D–A^D–B^D–A^D) and (B^D–A^D–A^D–A^D–B^D) with outer layers of densified veneers was equal (7.0 mm). This effect of veneer wood species on the thickness of plywood samples was mainly explained by the difference in the density of alder and birch wood. Birch veneer, having a higher density, is compressed less (8.2%) than alder veneer (11.5%), and, accordingly, formed thicker plywood samples. Moreover, the effect of the birch veneer on the formation of panel thickness was more pronounced when a denser birch veneer was placed in the outer layers of the panel. The smallest thicknesses (6.7–7.2 mm) of plywood samples were in samples made from densified veneer, and the greatest thicknesses (7.0–7.4 mm) were in the samples made from non-densified veneer (Table 3, Figure 1); however, the difference between them was significant. Plywood, in which the share of densified veneer (D) was greater, had a smaller thickness than plywood with a greater share of non-densified veneer (N), although the difference between them was insignificant.

The combination of wood species in one panel had a much stronger effect ($F = 101.404$) on the density of plywood samples than the combination of the type of treated veneer ($F = 13.334$) (Table 4). Plywood samples (A^N–A^N–A^N–A^N–A^N) made from non-densified alder veneer had the lowest density (583 kg/m^3), while samples (B^D–B^D–B^D–B^D–B^D) made from densified birch veneer had the highest density (832 kg/m^3). The predominance of non-densified alder veneer in one panel (60%) provided a lower density of 684 kg/m^3 and 661 kg/m^3 for plywood samples (B^N–A^N–A^N–A^N–B^N) and (A^N–B^N–A^N–B^N–A^N), respectively, in comparison to the density of 779 kg/m^3 for a birch-only plywood (B^N–B^N–B^N–B^N–B^N). However, these densities were greater than the density of 583 kg/m^3 obtained for the alder-only plywood (A^N–A^N–A^N–A^N–A^N). A similar trend was observed for the densified veneer. It is obvious that the density of the birch veneer was greater than the density of the alder veneer. The effect of the type of veneer treatment (N and D) and its combination on the density of plywood samples was not as strong as the effect of the wood species of the veneer (Table 4). With the same schemes of veneer assembly of different species in one panel, plywood samples with a densified veneer in the outer layers provided a greater density of plywood samples compared to samples comprising non-densified veneers. With the same assembly scheme of veneer and different wood species in one panel, increasing the proportion of densified veneer in the panel, in particular in the outer layers, reduced the density of sample (B^D–A^N–A^N–A^N–B^D) to 673 kg/m^3, compared to the density of 684 kg/m^3 obtained for sample (B^N–A^N–A^N–A^N–B^N), which was made from non-densified veneer only. However, the difference between the densities was insignificant. Meanwhile, the addition of densified veneer in the outer layers of sample (A^D–B^N–B^N–B^N–A^D) led to an increase in density to 726 kg/m^3 compared to the density of 709 kg/m^3 obtained for sample (A^N–B^N–B^N–B^N–A^N), which was made from non-densified veneer only. The higher *CR* and *DR* of alder veneer than birch veneer explained this (Table 2).

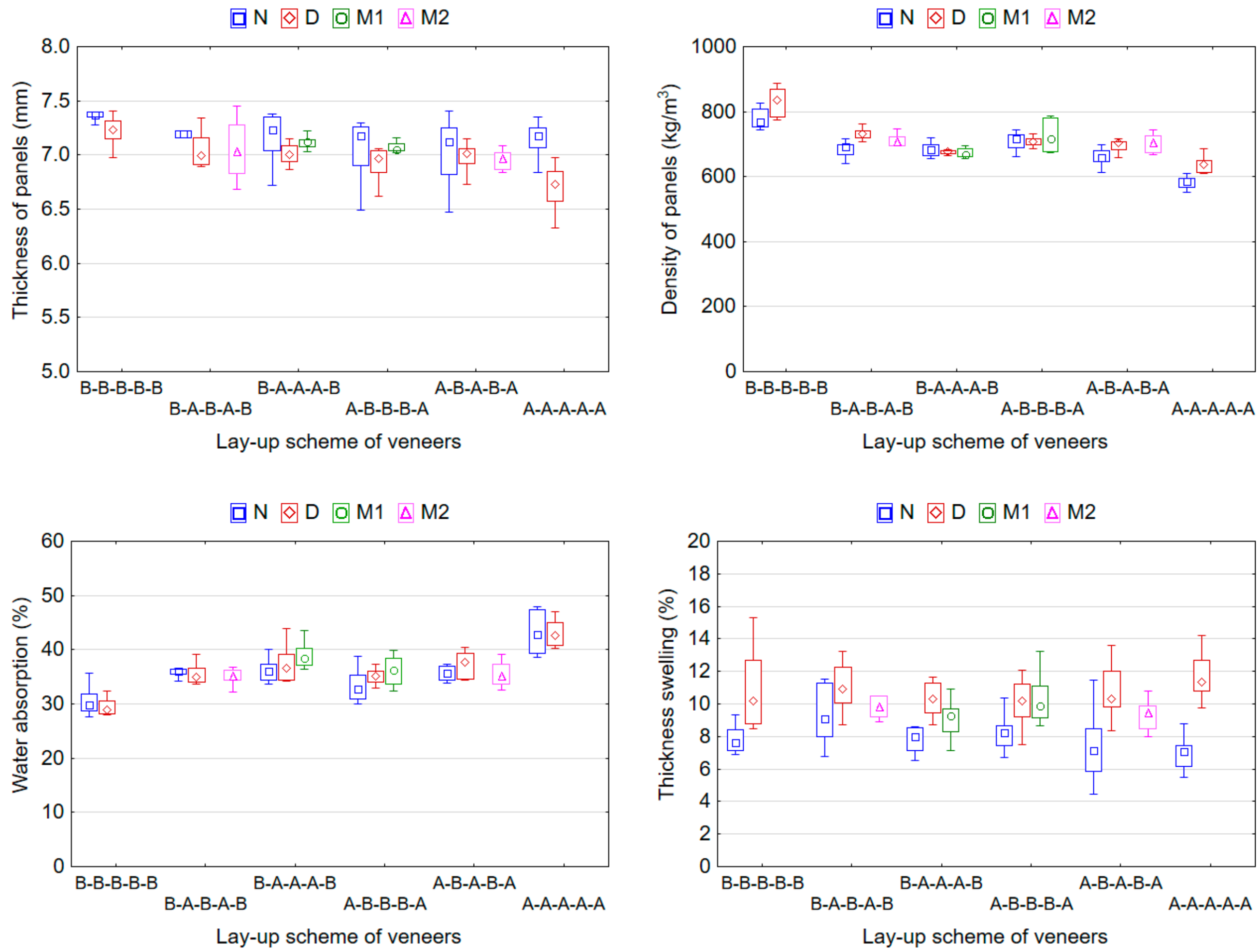

Figure 1. Effect of wood veneer species and type of veneer treatment on the physical properties of plywood panels. N—non-densified veneers in one panel; D—densified veneer in one panel; M1—mix of veneers (D–N–N–N–D) in one panel; M2—mix of veneers (D–N–D–N–D) in one panel; Statistical features are median, 25% minimum and 75% maximum.

The combination of different wood species and different types of veneer treatment in one plywood panel significantly affected the *WA* of plywood samples. In addition, the combination of veneers from different wood species in one panel had a much stronger effect (F = 51.493) on *WA* than the type of veneer treatment used (a combination of densified and non-densified veneer in one panel) (F = 4.148) (Table 4). The lowest and highest *WA* values of 29.3% and 43.0% were in plywood samples made from densified birch veneers (B^D–B^D–B^D–B^D–B^D) and non-densified alder veneers (A^N–A^N–A^N–A^N–A^N), respectively. With an increase in the proportion of alder veneer in the inner layers of birch plywood made from non-densified veneer (B^N–A^N–B^N–A^N–B^N and B^N–A^N–A^N–A^N–B^N), the *WA* increased and its value was significantly higher (36.3% for B^N–A^N–B^N–A^N–B^N and B^N–A^N–A^N–A^N–B^N) than the value 30.4% for the *WA* of a birch-only plywood made from non-densified veneer (B^N–B^N–B^N–B^N–B^N). However, the addition of birch veneers to the inner layers of an alder plywood resulted in a reduction in the *WA* of plywood made from alder only. A similar trend was observed for plywood panels made from densified veneer (Table 3, Figure 1). An increase in the proportion of densified veneer in one panel led to a decrease in the *WA* of plywood samples. This was explained by the density of plywood samples. It is well known that there is a relationship between *WA* and panel density [38]. The dependence of *WA* on the density of plywood panels is shown in Figure 2a. As the density of plywood samples increases, their *WA* decreases, as the number and size of available cavities through which water can enter the sample decreases. Several authors [27] also showed that *WA* is related to panel density, with a higher density resulting in a lower number of pores and, consequently, a lower *WA*.

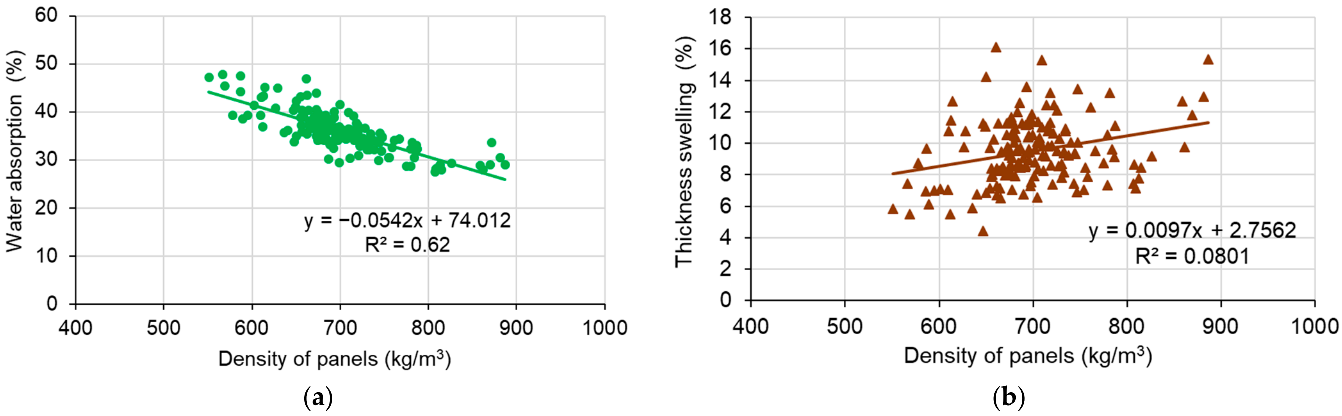

Figure 2. Influence of density on water absorption (**a**) and thickness swelling (**b**) of plywood samples.

The combination of veneers of different wood species in one panel had no effect on the *TS*, while the type of veneer treatment had a significant effect on the *TS* (Table 4). The lowest (7.2%) and highest (12.1%) values of *TS* were found in alder plywood samples made from non-densified (A^N–A^N–A^N–A^N–A^N) and densified (A^D–A^D–A^D–A^D–A^D) veneers, respectively. The mixed-species plywood samples using only densified veneers had a higher *TS* than samples using only non-densified veneers (Table 3, Figure 1). Increasing the share of densified veneer in one panel led to an increase in the *TS* of the mixed-species plywood samples. In this case, this was explained by the increase in the density of plywood samples. This is well known from sources in the literature [12,27,38]. However, in this study, no clear dependence of *TS* on sample density was found (Figure 2b).

The surface roughness of plywood panels with outer layers of non-densified and densified birch and alder veneer was also compared (Figure 3). In addition to the fact that plywood with outer layers of alder veneer had lower values of MOR and MOE (Table 5), the surface of such plywood also had a greater surface roughness compared to the birch plywood (Figure 3). It was found that for plywood made of non-densified alder veneer (A^N–A^N–A^N–A^N–A^N), the roughness parameters R_a and R_q were 19.4% and 5.4% greater, respectively, than the similar parameters for plywood made of non-densified birch veneer (B^N–B^N–B^N–B^N–B^N). On the contrary, the roughness parameter R_z for plywood made of non-densified alder veneer was 18.3% lower than for plywood made of non-densified birch veneer. For plywood made of densified alder veneer, the roughness parameters R_a, R_z and R_q were 41.6%, 0.4% and 14.2% higher than similar parameters for plywood made of densified birch veneer, respectively. This was logical, as birch wood has less porosity than alder wood. However, the differences in R_a, R_z and R_q found between non-densified/densified birch and alder veneers were statistically insignificant. Nevertheless, the thermal compression led to a decrease in the surface roughness values for both the birch and alder veneers. In our previous work [10], we also found that the surface of wood veneers became smoother and roughness values decreased significantly due to the thermal densification process.

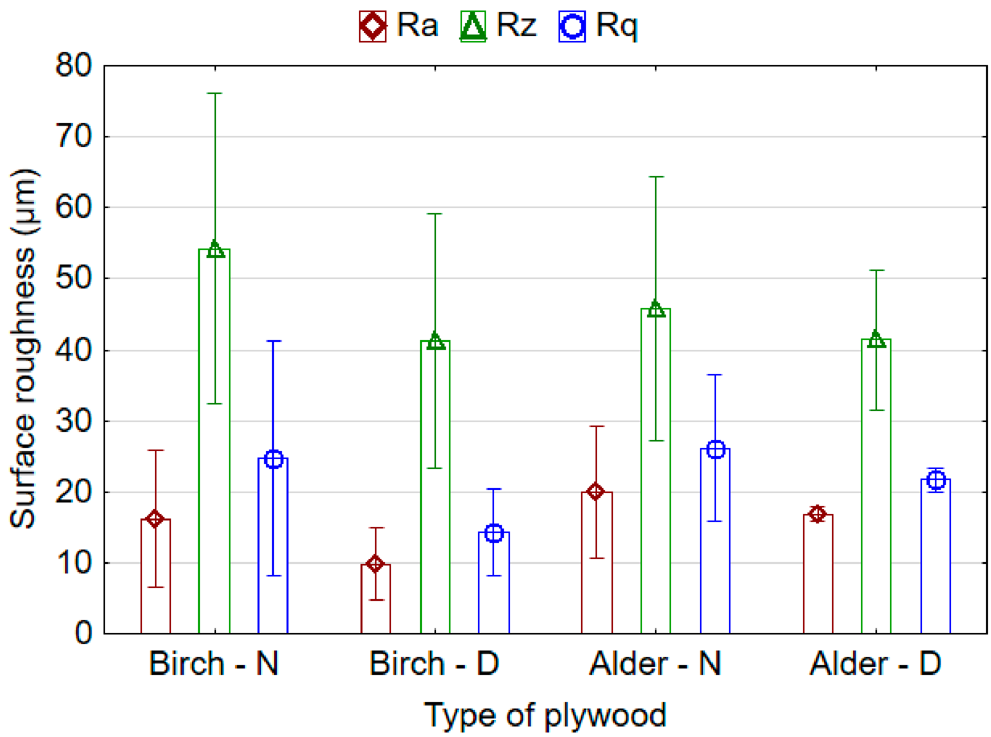

Figure 3. Surface roughness of plywood panels. N—non-densified veneers in surface layers; D—densified veneer in surface layers.

Table 5. Values of mechanical properties for plywood samples.

Code of Panels	Type of Panels	MOR (MPa)	MOE (MPa)	Shear Strength (MPa)
I	$B^N–B^N–B^N–B^N–B^N$	110 ^{d} (10)	12405 ^{f} (405)	2.8 ^{bc} (0.6)
II	$B^N–A^N–B^N–A^N–B^N$	97^c (17)	9765 ^{cd} (1644)	3.2 ^{cde} (0.5)
III	$B^N–A^N–A^N–A^N–B^N$	101 ^{cd} (10)	11,033 ^{e} (996)	2.9 ^{cd} (0.6)
IV	$A^N–B^N–B^N–B^N–A^N$	75 ^{a} (8)	7934 ^{a} (1363)	3.7 ^{fg} (0.5)
V	$A^N–B^N–A^N–B^N–A^N$	88 ^{b} (14)	9392 ^{bc} (1583)	3.0 ^{cde} (0.8)
VI	$A^N–A^N–A^N–A^N–A^N$	75 ^{a} (5)	8103 ^{a} (648)	2.9 ^{cd} (0.6)
VII	$B^D–A^N–A^N–A^N–B^D$	99 ^{c} (8)	10,893 ^{e} (798)	3.4 ^{ef} (0.6)
VIII	$A^D–B^N–B^N–B^N–A^D$	73 ^{a} (6)	8644 ^{ab} (1221)	3.7 ^{fg} (0.6)
IX	$B^D–A^N–B^D–A^N–B^D$	105 ^{cd} (8)	10,970 ^{e} (785)	3.3 ^{def} (0.8)
X	$A^D–B^N–A^D–B^N–A^D$	79 ^{a} (7)	8796 ^{abc} (1170)	3.8 ^{g} (0.7)
XI	$B^D–B^D–B^D–B^D–B^D$	119 ^{e} (14)	12,290 ^{f} (1409)	3.2 ^{cde} (0.6)
XII	$B^D–A^D–B^D–A^D–B^D$	102 ^{cd} (11)	10,758 ^{de} (557)	2.2 ^{a} (0.2)
XIII	$B^D–A^D–A^D–A^D–B^D$	101 ^{cd} (5)	10,670 ^{de} (995)	3.2 ^{cde} (0.3)
XIV	$A^D–B^D–B^D–B^D–A^D$	79 ^{a} (5)	8913 ^{abc} (717)	3.2 ^{cde} (0.6)
XV	$A^D–B^D–A^D–B^D–A^D$	80 ^{ab} (7)	9361 ^{bc} (691)	3.7 ^{fg} (0.5)
XVI	$A^D–A^D–A^D–A^D–A^D$	78 ^{a} (9)	8345 ^{ab} (1111)	2.5 ^{ab} (0.5)

Values in parentheses are standard deviations; means followed by the same letter are not significantly different at $p \leq 0.05$.

3.3. Mechanical Properties of Plywood Samples

The mechanical properties of plywood samples, which were made by combining veneers of different wood species and different types of treatment in one panel, are summarized in Table 5. The highest (119 MPa) and lowest (73 MPa) values of MOR were observed in plywood samples ($B^D–B^D–B^D–B^D–B^D$), a panel made of densified birch veneer, and ($A^D–B^N–B^N–B^N–A^D$), a panel with outer layers of densified alder veneer and inner layers of non-densified birch veneer, respectively. The highest (12,405 MPa) and lowest (7934 MPa) values of MOE were found in plywood samples ($B^N–B^N–B^N–B^N–B^N$), a panel made of non-densified birch veneer, and ($A^N–B^N–B^N–B^N–A^N$), a panel with external layers of non-densified alder veneer and internal layers of non-densified birch veneer, respectively. The highest (3.8 MPa) and lowest (2.2 MPa) shear strength values were observed in plywood samples (A^D–B^N–A^D–B^N–A^D) and (B^D–A^D–B^D–A^D–B^D), respectively. Thus, the highest shear strength was observed between densified alder veneer and non-densified birch veneer (A^D–B^N–A^D–B^N–A^D). The lowest shear strength was found between a densified birch and densified alder veneer (B^D–A^D–B^D–A^D–B^D).

The ANOVA analysis showed (Table 6) that combining veneers of different wood species in one panel had a significant effect on the MOR and MOE, while combining different types of veneer treatment had an insignificant effect on the MOR and MOE. The mixed-species plywood panels manufactured from densified veneers had a higher MOR and MOE than panels made from non-densified veneers (Table 5, Figure 4). The mixed-species plywood panels made with outer layers comprising birch veneers (non-densified or densified) had higher MOR and MOE than panels made with outer layers comprising alder veneers (non-densified or densified). At the same content of birch and alder veneers in one panel (samples that included non-densified veneers B^N–A^N–B^N–A^N–B^N and A^N–B^N–B^N–B^N–A^N, or samples that included densified veneers B^D–A^D–B^D–A^D–B^D and A^D–B^D–B^D–B^D–A^D), plywood with outer layers of birch veneer had about 22% and 18% higher MOR and MOE, respectively, when compared to plywood with outer layers of alder veneer. The birch plywood panels made from non-densified or densified veneers had higher MOR and MOE than alder panels made from non-densified or densified veneers. Birch plywood samples made from non-densified (B^N–B^N–B^N–B^N–B^N) or densified (B^D–B^D–B^D–B^D–B^D) veneer had 31.5% and 34.8% higher MOR, and 34.7% and 32.1% higher MOE than alder plywood samples made from non-densified (A^N–A^N–A^N–A^N–A^N) or densified (A^D–A^D–A^D–A^D–A^D) veneers, respectively. This was explained by the higher strength and density of birch wood compared to alder wood. However, the difference between the MOR values for mixed-species plywood samples (B^N–A^N–A^N–A^N–B^N, B^N–A^N–B^N–A^N–B^N, B^D–A^D–A^D–A^D–B^D and B^D–A^D–B^D–A^D–B^D) made from non-densified or densified veneers was insignificant, so in practice, during the manufacture of birch plywood, alder veneers can be used to form the inner layers without deteriorating the MOR of the plywood. Similar results were obtained in the research conducted by Bal [19], in which seven-ply LVL panels were manufactured from fast-growing poplar veneers and used as the inner layers, while eucalyptus veneers were used as the outer layers. The author demonstrated that using two eucalyptus veneers on the faces significantly increased the MOE (30%) and MOR (12%) in comparison to poplar-only LVL panels. In another work [26] where seven-ply LVL panels were manufactured by combining higher-density Austrian pine veneers and lower-density Lombardy poplar veneers, it was found that as the share of pine veneers increased in the mixed-species panels, the MOR and MOE increased by up to 40% and 69% on average, compared to panels manufactured only with poplar. Xue and Hu [17] also found that the strength of the LVL made of birch veneers on the outer surface was much greater than the LVL made of poplar veneers.

Table 6. The influence of the variable factors on the mechanical properties of plywood.

Source of Variation	MOR		MOE		Shear Strength	
	F	**Sig.**	***F***	**Sig.**	***F***	**Sig.**
W	62.765	0.000	48.591	0.000	12.048	0.000
T	0.998	0.396	0.782	0.506	9.562	0.000
W × T	1.881	0.077	1.825	0.086	7.326	0.000

W—combination of veneers of different wood species; T—combination of veneers with different treatments used.

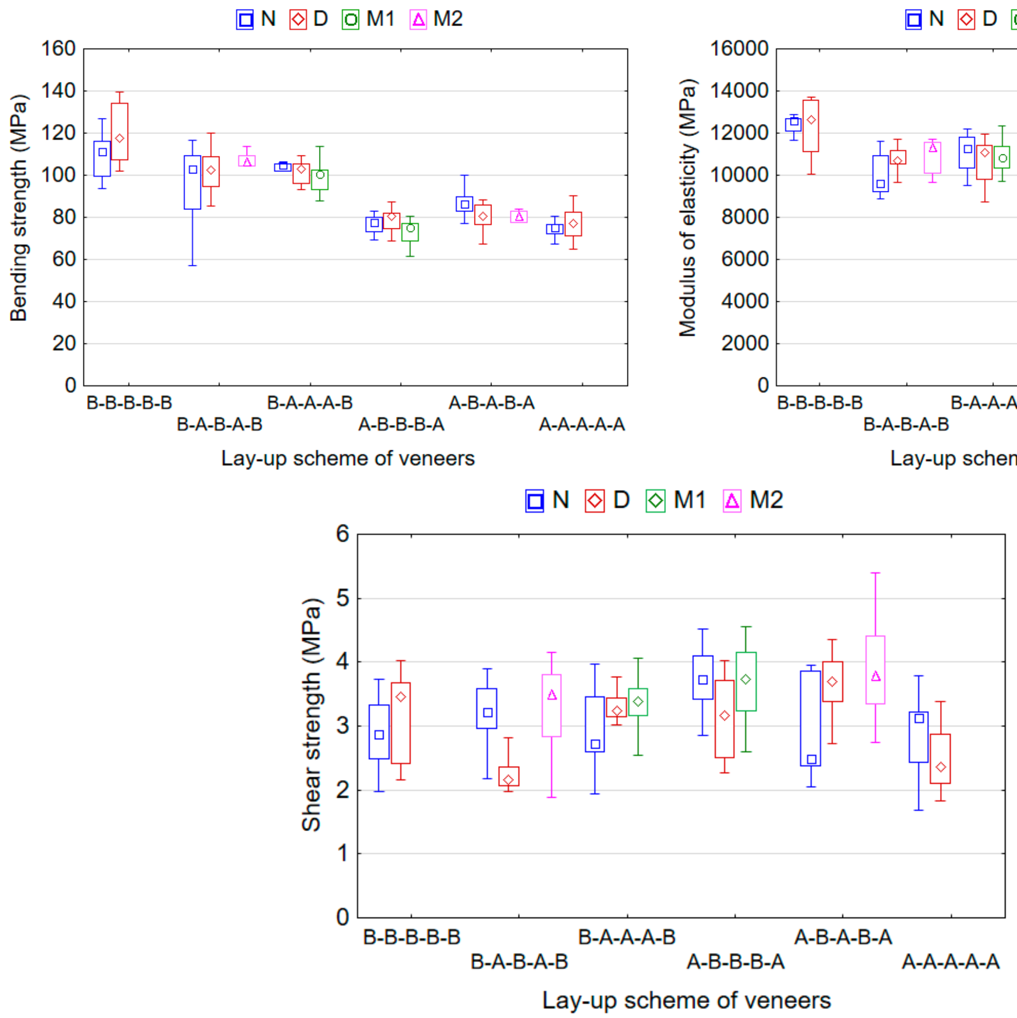

Figure 4. Effect of wood veneer species and type of veneer treatment on the MOR, MOE and shear strength of plywood panels. N—non-densified veneers in one panel; D—densified veneer in one panel; M1—mix of veneers (D–N–N–N–D) in one panel; M2—mix of veneers (D–N–D–N–D) in one panel. Statistical features are median, 25% minimum and 75% maximum.

Figure 5 shows the linear dependence of the MOR and MOE of plywood samples on their density. These dependences were not strong, which indicates that, in addition to density, other factors, such as the veneer thickness, species and type and amount of adhesive used, affected the MOR and MOE. In another work [39], it was also observed that the MOR and MOE of plywood panels made from densified and non-densified veneers increased when the density increased.

With an increase in the proportion of alder veneer in the inner layers of birch plywood made from non-densified veneers (B^N–A^N–B^N–A^N–B^N and B^N–A^N–A^N–A^N–B^N), the MOR and MOE increased, although its values were lower (97 MPa and 9765 MPa for B^N–A^N–B^N–A^N–B^N, respectively; 101 MPa and 11033 MPa for B^N–A^N–A^N–A^N–B^N, respectively) than the MOR and MOE values of 110 MPa and 12405 MPa, respectively, obtained for plywood made from birch alone (B^N–B^N–B^N–B^N–B^N). The addition of birch veneer to the inner layers of an alder plywood also led to an increased MOR and MOE. A similar trend was observed for plywood panels made from densified veneers. An increase in the proportion of densified veneer in one panel contributed to an increase in the MOR and MOE. Densified veneer had a higher density than non-densified veneer. It is known that MOR and MOE increases with increasing density [39]. This was in good agreement with the linear relationship between density and both MOR and MOE obtained in this study (Figure 5).

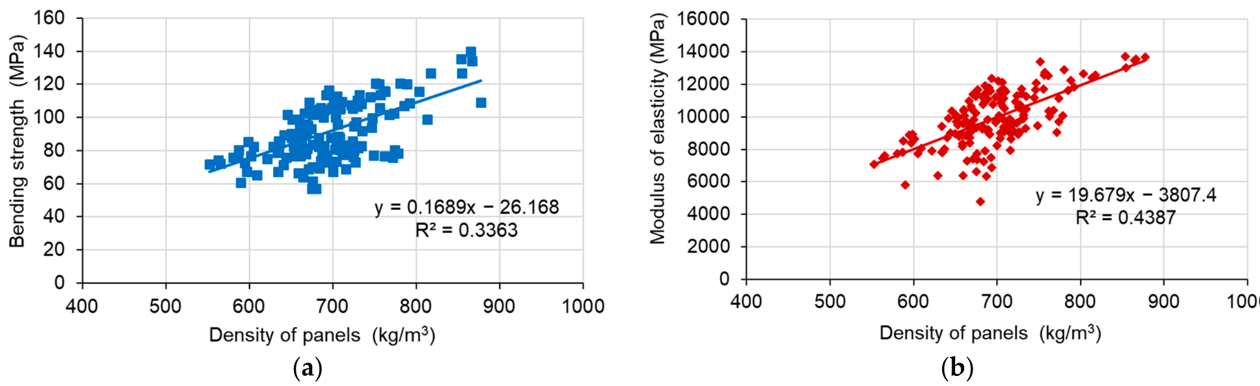

Figure 5. Dependence of bending strength (**a**) and modulus of elasticity (**b**) of plywood samples on their density.

Combinations of different wood species and types of veneer treatment in one panel significantly affected the shear strength of plywood samples (Table 6). In addition, the effect of wood species was stronger (F = 12.048) than the effect of the type of veneer treatment used (F = 9.562). It was found that there was no significant difference ($p > 0.05$) in shear strength values (2.8 MPa and 2.9 MPa, respectively) between birch (B^N–B^N–B^N–B^N–B^N) and alder (A^N–A^N–A^N–A^N–A^N) plywood panels made from non-densified veneers. However, a significant difference ($p \leq 0.05$) in shear strength values (3.2 MPa and 2.5 MPa, respectively) was observed between birch (B^D–B^D–B^D–B^D–B^D) and alder (A^D–A^D–A^D–A^D–A^D) plywood panels made from densified veneers. When the cut was along the birch (the second sheet-layer of veneer in one panel), the strength was higher, while the strength was lower when the cut was along the alder (the second sheet-layer of veneer in one panel). However, in this study, all plywood composed of densified and non-densified veneers still met the requirements (>1.0 MPa) of EN 314-2 [32]. This showed that all the combinations with high-density birch veneer and low-density alder veneer bonded well.

From the obtained experimental results, it can be observed that the addition of alder veneer to the inner layers of birch plywood had a positive effect on the shear strength, increasing it compared to the strength of a birch-only plywood made from non-densified veneer. Similarly, the addition of birch veneer to the inner layers of an alder plywood made from both non-densified or densified veneers led to an increased shear strength.

Higher values of shear strength were observed in mixed-species plywood panels with alternating sheets of densified and non-densified veneers in adjacent layers (panels B^D–A^N–A^N–A^N–B^D, A^D–B^N–B^N–B^N–A^D, B^D–A^N–B^D–A^N–B^D and A^D–B^N–A^D–B^N–A^D). In our previous work [27], it was also observed that using densified veneers increased the mechanical performance of plywood panels, but worsened the *TS* and *WA* of panels.

Some authors [1,40] have affirmed that the density of wood is an important factor that affects the formation of an adhesive bond between veneers. In their opinion, low-density woods will absorb a larger quantity of adhesive, due to its higher porosity. Based on this, it can be assumed that when non-densified veneer is in contact with another non-densified veneer (N–N), more adhesive is absorbed by the two surfaces to be bonded and less adhesive remains on the surfaces to be bonded. Starvation bonding may occur in this case. When densified veneer is in contact with non-densified veneer (D–N), it can be expected that less adhesive will be absorbed by the densified surface (due to its lower porosity) and more adhesive will remain between the bonded surfaces. This will ensure a good bonding strength and prevent "hungry" bonding. In addition, it should be taken into account that birch and alder veneers have a different density and porosity.

Microscopic images of a bond line in birch and alder plywood are presented in Figures 6 and 7.

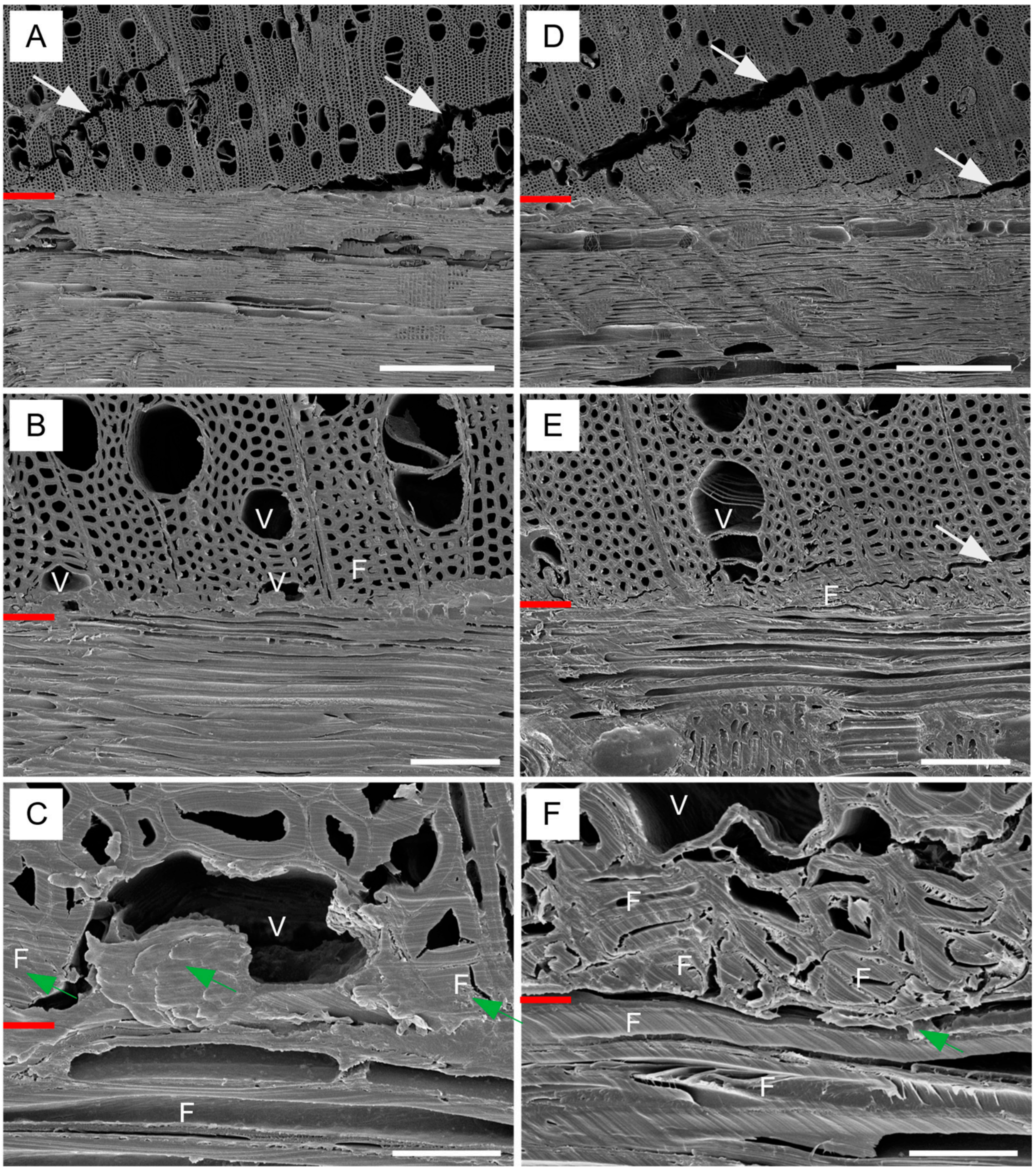

Figure 6. SEM observation of bond line in birch plywood. (**A**–**C**)—non-densified veneers (panel I); (**D**–**F**)—densified veneers (panel XI); V—vessel, F—fiber, red line—bond line, white arrow—crack, green arrow—glue. Scale bar: (**A**,**D**) = 500 µm, (**B**,**E**) = 100 µm, (**C**,**F**) = 20 µm.

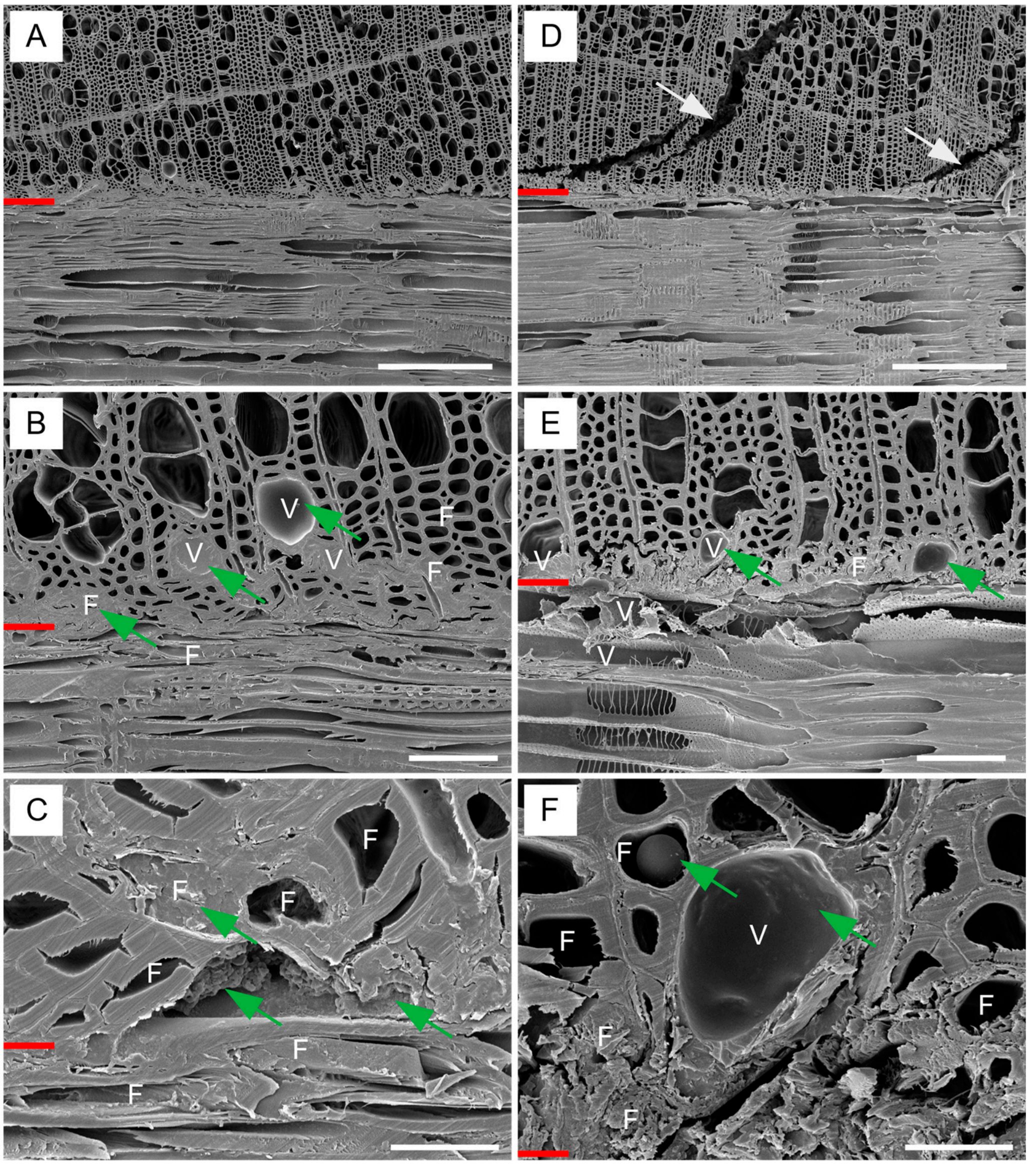

Figure 7. SEM observation of bond line in alder plywood. (**A**–**C**)—non-densified veneers (panel VI); (**D**–**F**)—densified veneers (panel XVI); V—vessel, F—fiber, red line—bond line, white arrow—crack, green arrow—glue. Scale bar: (**A**,**D**) = 500 µm, (**B**,**E**) = 100 µm, (**C**,**F**) = 20 µm.

Figure 6 shows that the birch wood had a smaller percentage of vessels compared to the alder (Figures 6A and 7A). Wagenführ [41] stated that the number of vessels in birch wood ranges from 40 to 60 per 1 mm^2, while in the case of alder wood the number of vessels is 75–145 per 1 mm^2; there was also a difference in the porosity of the woods, with 59% in birch compared to 71% in alder. The arrangement of the anatomical elements and their morphometric parameters influenced the resulting penetration of the glue from the bond line into the deeper layers of the veneer. The bond line in non-densified birch veneers was thin and the glue did not penetrate into the deeper layers of the glued veneers (Figure 6B,C). The penetration of glue into the deeper layers of the densified veneer was additionally prevented by a layer of compressed fibers and vessels (Figure 6F). The densification process of the veneer surface layers resulted in deformed anatomical elements and eliminated lumens. The densification of the surface layers of birch veneers was also manifested by a reduction in the surface roughness (Figure 3).

Figure 7 shows a bond line in alder plywood made from non-densified and densified veneers. The alder wood had a higher number of vessels than the birch, and the wood fibers were thin-walled (Figure 7A,B). The higher porosity of the alder wood, thus, enabled an easier penetration of the glue into the deeper layers of the veneer (Figure 7B,C). In the case of densified alder veneers, there was also a distinct layer of deformed fibers and vessels. The densification of the surface layers, as in the case of birch, prevented the penetration of the glue into the deeper layers of the veneer, and the bond line was, therefore, thinner. In both types of wood panels, it was possible to observe distinct microscopic cracks that occurred when the veneer was peeled off (Figure 6A,B and Figure 7D).

4. Conclusions

The results showed that the type of construction, wood species and applied thermal densification of the veneer affected the examined physical and mechanical properties. According to the ANOVA analysis, the *WA*, MOR, MOE and shear strength of plywood were more sensitive to the mixing of wood species in one panel than the mixing of densified and non-densified veneers. Moreover, the results indicated the great potential of black alder wood in plywood manufacturing. Alder veneers can be used to form the inner layers of plywood panels without reducing the shear strength. The B^D–A^N–B^D–A^N–B^D and B^D–A^N–A^N–A^N–B^D panels were determined to be the most reasonable lay-up schemes when the shear strength, MOR and MOE values of mixed-species plywood panels manufactured were examined.

The plywood thicknesses for all types of panel were in the range 6.7–7.4 mm and they did not go beyond tolerances for unsanded panels in accordance with standard EN 315.

Increasing the proportion of thermally densified veneer in one panel led to a lower thickness and *WA*, but higher density, MOR, MOE, shear strength and *TS* of plywood panels. It is important to note that positive effects can be achieved not only by increasing the proportion of densified veneers in one panel, but also with a change of construction by mixing the wood species used.

Plywood with outer layers of alder veneer had a lower bending strength than plywood with outer layers of birch veneer. Alder plywood with inner layers of birch veneer or adjacent birch and alder veneers in the core had a lower MOR and MOE, but higher shear strength than birch plywood with inner layers of alder veneer or adjacent alder and birch veneers in the core. It was found that plywood panels manufactured from a mixture of species offered higher bending properties when compared to panels manufactured from alder veneers only.

For single-species plywood panels, the birch plywood performed best in terms of MOR, MOE, shear strength and *WA*, while the alder plywood performed the worst. The negative influence of the alder veneer was attenuated by combining the densified and non-densified veneer, and having alder and birch veneers in one panel. The mixed-species plywood panels allowed an increased use of the lower cost, low-grade, and low-density alder wood veneers as core veneers in panels to reduce production costs and increase the mechanical properties of predominately low-density alder wood plywood.

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