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Wood plastic composites as a substitution for HDF

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Abstract: *Wood plastic composites as a substitution for HDF*. As part of the research, industrial HDF boards were used and WPC composites were produced, differentiated in terms of matrix (PLA and HDPE) and filler content (40%, 50% and 60%). The density and density profile was measured to compare HDF and WPC structure. In addition, the manufactured boards were tested for strength (MOR, MOE), screw holding, thickness swelling and water absorption after immersion in water for 2 and 24 hours. WPC were characterized by a higher density than HDF boards and a uniform density profile. In addition, WPC composites were characterized by lower MOR and MOE values than HDF boards. Compared to HDF boards, WPC composites were characterized by higher values of screw holding and better resistance to moisture.

Keywords: WPC, composites, PLA, mechanical properties, physical properties

INTRODUCTION

High density fibreboards (HDF) belong to the fibreboards produced by the dry method. Density of HDF is generally in the range of 700 - 900 kg/m^3, but there are also thin high density fiberboards (THDF) varieties with a density in the range of 900 - 1050 kg/m^3. The thickness of HDF boards does not exceed 8 mm, while THDF boards are manufactured in thicknesses of 1.6 - 6.0 mm (Nicewicz and Sala 2014). China is the world leader in the production of dry-formed fibreboards. According to the Food and Agriculture Organization of the United Nations data, the production of those boards in 2020 was 55,152 million m^3 (www.fao.org). In the same year, 20,800 million m^3 were produced in Europe. Poland, with a production of 3,550 million m^3 in 2020, was ranked second in Europe (www.fao.org). It is worth adding, that over the last 20 years in Poland there has been an increase in the production of dry-formed fibreboards by over 360%.

HDF and THDF boards are mainly used in the furniture industry (back walls of furniture, drawer bottoms, cell panel cladding) and construction (floor panels, door frame linings). A certain limitation in the use of HDF boards is their susceptibility to the effects of moisture. Wood-based materials show high hygroscopic properties, which result in free exchange of water vapor with the environment. The use of boards with increased resistance to water does not guarantee sufficient protection against the destructive effects of moisture and related degradation factors (Thoemen et al. 2010, Niemz and Sonderegger 2017). In general, it can be concluded that the properties of dry-formed fibreboards depend on the morphology of the wood fibers, the amount and type of chemicals added during production and the technological parameters used during the production of the boards. Park et al. (2001) showed that the best properties of MDF boards are obtained by using a mixture of coniferous and deciduous wood fibers. In Poland, the wood of coniferous species is mainly used for the production of fibreboards - pine, spruce (80-85%), with the addition of deciduous species - alder, birch (15-20%) (Nicewicz and Kowaluk 2017). While, Benthien et al. (2014) showed that as the length of the fibers increased, the mechanical properties of the panels improved and their physical properties deteriorated. In this context, Gul et al. (2017) also showed that the pressing temperature of the plates plays an important role. Its increase significantly improves the strength parameters and reduces the swelling and absorbability of the boards. An important role, in the context of the subsequent use of the boards, is also played by the type of adhesive resin used (UF, MUF, pMDI) as well as the degree of gluing of the boards (Dunki and Pizzi 2002). With the increase in the degree of sizing, the mechanical and physical properties of MDF boards improve (Hong et al. 2017). It is worth noting that the increase in the degree of sizing also increases the emission of formaldehyde, which is an undesirable effect. According to data from the European IPPC Bureau, in 2010 - 2011, on 13 production lines in Europe, 68% of MDF boards were produced with the use of UF resins (dry-resistant boards), 30% with the use of MUF resins, and PMDI resins were used as an additive in small quantities (Raunkjær Stubdrup et al. 2016). According to PN-EN 622-5, dry-formed fibreboards up to 2.5 mm thick can have a swelling value after 24 hours of immersion in water up to 45%.

A solution in this regard for applications in an environment with increased relative air humidity (e.g. as elements of bathroom or kitchen furniture) may be thin wood-polymer boards. The properties of WPC composites are mainly determined by the quantitative share of wood and thermoplastic particles, the size of wood particles, the type of thermoplastic, the addition of substances supporting joining and the production methods (Stark and Berger 1997, Błędzki and Faruk 2004). Most authors also point to the fact that composites achieve optimal strength properties with a content of wood particles in the range of 40-60% (Stark and Berger 1997, Chen et al. 2006, Borysiuk et al. 2004, 2008, Diporović et al. 2006). In general, WPC composites are characterized by lower MOR and MOE properties and comparable values of tensile and compressive strength. An important advantage of wood-polymer composites over other wood-based panels is their resistance to water (Falk et al. 1999, Sellers et al. 2000).

As part of the research, selected properties of wood-polymer boards were determined, determining the possibility of their use as a substitute for HDF boards for the production of furniture elements, in particular furniture used in conditions with the possibility of exposure to air with increased humidity or liquid water.

MATERIALS

As part of the research, industrial HDF boards with a nominal thickness of 2.5 mm and a density of 900 kg/m^3 and WPC composite boards with a thickness of 2.5 mm and a density of approx. 1000 kg/m^3, manufactured in laboratory conditions, were used. A total of 6 variants of WPC composite panels (Table 1) were produced based on two types of polymer matrices: polylactic acid - PLA (Ingeo™ Biopolymer 2003D, NatureWorks LLC, Minnetonka, MN, USA) and high-density polyethylene - HDPE (Hostalen GD 7255, Basell Orlen Polyolefins Sp. z o.o., Płock, Poland). Coniferous sawdust was used as a filler. The lignocellulosic material obtained from the sawmill was dried to a moisture content of 5% and then mechanically comminuted and sorted to particles passing through a 0.49 mm sieve (above 35 mesh).

Table 1. Characteristics of WPC composites variants

Variant	Matrix	Share of matrix	Share of filer
I	HDPE	60	40
II	HDPE	50	50
III	HDPE	40	60
IV	PLA	60	40
V	PLA	50	50
VI	PLA	40	60

The composites were produced in two stages:

1. in the first stage, WPC granulate with the appropriate formulation was produced (Table 1) - using an extruder (Leistritz Extrusionstechnik GmbH, Nürnberg, Germany) (temperatures in individual sections of the extruder were 170 ^{o}C - 180 ^{o}C) a continuous ribbon of the composite was obtained, which was then crushed into hammer mill;
2. in the second stage, boards with nominal dimensions of 300x300x2.5 mm^3 were produced from the obtained granulate by flat pressing in a mold, using a single-deck press (AB A.K. Eriksson, Mariannelund, Sweden) at a temperature of 200 ^{o}C and a maximum unit pressing pressure pmax = 1.25 MPa (the pressure during pressing was gradually increased from 0 to pmax as the material became plastic). The pressing time was 6 minutes. After hot pressing, the boards were cooled in the mold for 6 minutes in a cold press.

After production, the WPC boards were conditioned for 7 days in laboratory conditions (20 ± 2 ^{o}C, 65 ± 5% humidity).

For HDF boards and boards made of WPC, the following physical and mechanical properties were tested:

- density according to EN 323:1999 and density profile using Laboratory Density Analyser DAX GreCon (Fagus-Grecon Greten GmbH & Co. KG, Alfeld, Germany). Density measurement was made every 0.02 mm at the measurement speed of 0.05 mm/s;
- modulus of rupture (MOR) and modulus of elasticity (MOE) according to EN 310:1994;
- screw holding (SH) according to EN 320:2011
- thickness swelling (TS) and water absorption (WA) after 2h and 24h immersion in water – according to EN 317:1999.

10 samples for each of the variants were used to carry out the aforementioned tests. Statistical analysis of the results was carried out in Statistica version 13 (TIBCO Software Inc., CA, USA). Analysis of variance (ANOVA) were used to test (α=0.05) for significant differences between factors. A comparison of the means was performed by Tukey test, with α=0.05.

RESULTS

The tested boards were characterized by densities in the range of 1025 - 1076 kg/m^3 for the HDPE matrix and 1146 - 1152 kg/m^3 for the PLA matrix. The average density values for individual board variants are presented in Table 2. Density differences for individual variants within the same matrices (HDPE or PLA) did not exceed 5%. Higher density values of composites based on the PLA matrix in relation to the HDPE matrix resulted from the density of the thermoplastic. Similar relationships were obtained by Andrzejewski et al. (2019) examining WPC composites based on PLA and PP. In turn, in relation to HDF boards, the composites were characterized by a density higher by 15 – 21% for the HDPE matrix and 29% for the PLA matrix. All variants of the tested composites, compared to HDF boards, were generally characterized by uniform density distribution over the cross-section (fig. 1). Density differences in the thickness of individual boards did not exceed 200 kg/m^3. In contrast to the HDF boards, where the density profile was typical U-shaped, the composite boards showed a uniform decrease in density in the middle zone of the board. A similar effect of density decrease in WPC composites was presented by Borysiuk et al. (2019). The uniform course of the density profiles of the composites indicated a good homogenization of the composite components and an even distribution of the filler particles in the polymer matrix.

Table 2. Density of tested boards

Variant	Matrix/board	Filler share [%]	Density [kg/m^3]	Standard Deviation [kg/m^3]
I	HDPE	40	1025 ^{b}	25
II	HDPE	50	1039 ^{b}	41
III	HDPE	60	1076 ^{b}	25
IV	PLA	40	1152 ^{c}	56
V	PLA	50	1146 ^{c}	62
VI	PLA	60	1148 ^{c}	56
VII	HDF	-	891 ^{a}	24

a, b, c - homogeneous groups by Tukey test (α = 0.05)

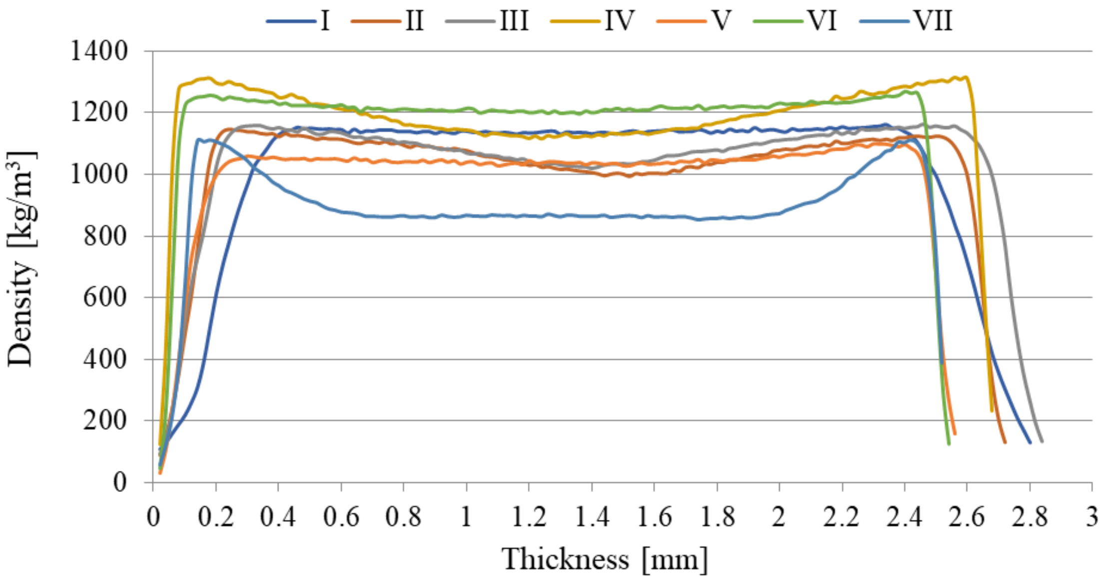

Figure 1. Density profile of tested composites

The results of the tests of the mechanical properties of the boards are shown in Figs. 2, 3 and 4. In general, it should be stated that the WPC boards were characterized by lower MOR and MOE values compared to HDF boards. This is consistent with the data presented by Falk et al. (1999). It is worth noting, that a greater decrease in the MOR and MOE values in relation to HDF boards was recorded in the case of HDPE-based boards. It was 58 - 71% for MOR and 62 - 68% for MOE, respectively (Figs 2, 3). For PLA-based boards, the decrease in value was respectively 10 - 71% for MOR and 9 - 68% for MOE (Figs 2, 3). Higher strength parameters for PLA-based boards compared to HDPE-based boards result from the higher stiffness of PLA compared to polyolefins (Gurunathan et al. 2015). Irrespective of the type of thermoplastic, the increase in the content of lignocellulosic particles resulted in a decrease in the MOR and MOE values of the tested boards. The observed dependencies correspond to the data presented in the literature. Stark and Berger 1997, Błędzki and Faruk 2004, Lee et al. 2004 or Cui et al. 2008 report that with a decrease in the content of wood particles in the composite (regardless of their size), the MOR and MOE values decrease, while the tensile strength increases.

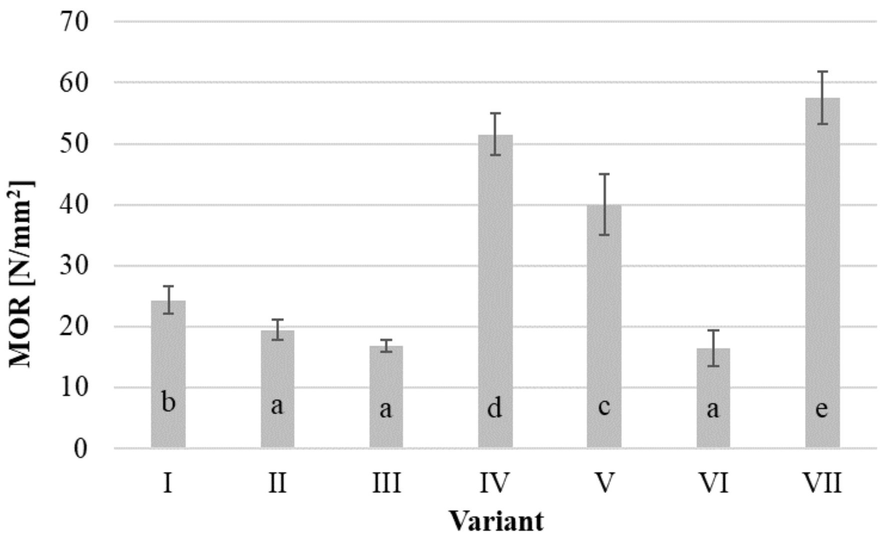

Figure 2. Modulus of rapture tested boards. (a, b, c, d, e - homogeneous groups by Tukey test (α = 0.05)).

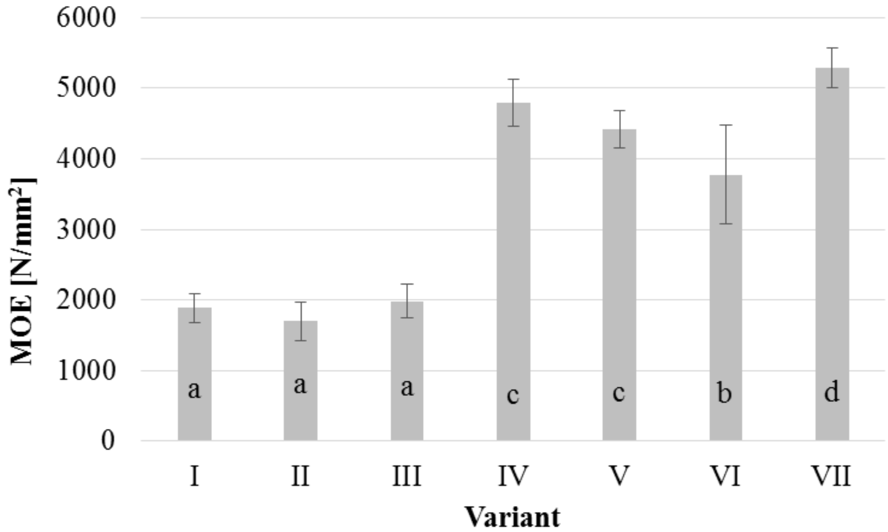

Figure 3. Modulus of elasticity tested boards. (a, b, c, d, e - homogeneous groups by Tukey test (α = 0.05)).

HDF boards, compared to WPC boards, were generally characterized by lower screw holding values (Fig. 4). This dependence was observed at 40 and 50% of the content of lignocellulosic particles in the polymer matrix (variants I, II, IV and V). In these cases, HDF boards were characterized by lower screw holding values by 30 - 37% in relation to HDPE-based boards and by 75 - 89% in relation to PLA-based boards. The observed dependencies correspond to the data presented in the literature (Carroll et al. 2001, Falk et al. 2001, Kociszewski et al. 2007, Gozdecki and Kociszewski 2008, Borysiuk et al. 2011). Taking into account the type of thermoplastic (with a filler content of 40 and 50%), PLA-based boards were characterized by an average of 27% higher screw holding values compared to HDPE-based boards. As in the case of the MOR and MOE values, this is related to the higher stiffness of PLA (Gurunathan et al. 2015). Similar dependencies were also obtained by Borysiuk et al. 2021a.

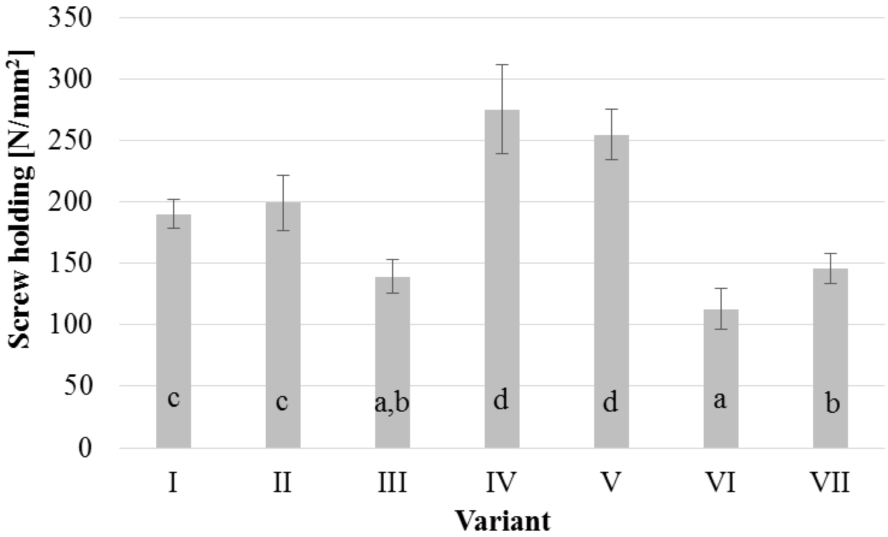

Figure 4. Screw holding tested boards. (a, b, c, d, e - homogeneous groups by Tukey test (α = 0.05)).

An important advantage of the tested WPC composites in relation to HDF boards is their definitely higher resistance to moisture. The results of swelling and water absorption of the tested boards are presented in Tables 3 and 4. Maximum resistance to moisture is achieved by variants of WPC boards with the lowest content of lignocellulosic particles (variants I and IV). Compared to HDF boards, they were characterized by over 90% lower values of swelling and water absorption both after 2 and 24 hours of soaking. The increase in the content of lignocellulosic particles in the WPC composites resulted in an increase in the value of their swelling and water absorption. Larger changes were noted in the case of boards made on the basis of PLA. Similar relationships were presented in the works of Borysiuk et al. (2021b) and Borysiuk and Auriga (2022). It should be noted here, that even with the content of 60% of lignocellulosic particles in WPC composites, they were characterized by swelling and water absorption values after 24 hours of soaking, compared to HDF boards, by over 85% lower in the case of boards based on HDPE and over 60% lower for PLA-based boards.

Table 3. Thickness swelling test results

Variant	Thickness swelling after 2 h immersion in water [%]		Thickness swelling after 24 h immersion in water [%]	
	Average	St. Dev.	Average	St. Dev.
I	0.41 [a]	0.13	1.18 [A]	0.18
II	0.40 [a]	0.11	2.01 [AB]	0.34
III	1.76 [b]	0.28	5.28 [D]	0.77
IV	0.78 [ab]	0.13	3.30 [BC]	0.69
V	1.90 [b]	0.37	4.63 [CD]	0.86
VI	7.32 [c]	1.38	14.08 [E]	2.49
VII	14.62 [d]	1.66	38.61 [F]	1.67

a,b,c,d A,B,C,D,E,F – homogeneous groups by Tukey test (α = 0.05)

Table 4. Water absorption test results

Variant	Water absorption after 2 h immersion in water [%]		Water absorption after 24 h immersion in water [%]	
	Average	St. Dev.	Average	St. Dev.
I	0.24 ^{a}	0.02	0.88 ^{A}	0.09
II	0.49 ^{ab}	0.07	2.60 ^{AB}	0.26
III	0.91 ^{abc}	0.15	4.55 ^{B}	0.61
IV	1.73 ^{bc}	0.31	4.61 ^{BC}	0.65
V	2.31 ^{c}	0.37	6.87 ^{C}	0.81
VI	6.51 ^{d}	0.79	19.94 ^{D}	2.15
VII	20.51 ^{e}	2.70	53.05 ^{E}	3.74

a,b,c,d,e A,B,C,D,E – homogeneous groups by Tukey test (α = 0.05)

Table 5. Analysis of variance for individual board variants

Property		p	X	Error
Density		0.00	79.5	20.5
MOR		0.00	96.5	3.5
MOE		0.00	94.6	5.4
Screw holding		0.00	88.7	11.3
Thickness	2h	0.00	97.5	2.5
swelling	24h	0.00	99.1	0.9
Water	2h	0.00	97.8	2.2
absorbability	24h	0.00	99.1	0.9

p – probability of error, X – percentage influence of factors on the examined property of particleboard

The analysis of variance showed that all the tested factors (type of board, type of matrix, share of lignocellulosic particles) had a statistically significant effect on the tested properties of the boards. It should also be noted that the percentage influence factor allows us to conclude that the tested factors are the main factors affecting the value of MOR, MOE, IB, thickness, swelling and water absorption of the manufactured boards (Table 5). The influence of possible factors not included in the research was relatively small (Error = 0.9 – 5.4%). Only in the case of screw holding (Error = 11.3%) and density (Error = 20.5%) there was a greater impact on the tested properties of possible factors not included in the tests.

CONCLUSIONS

Based on the tests of WPC boards and HDF boards of similar thickness, it can generally be concluded that WPC boards can be a substitute for HDF boards in non-structural applications, especially when used in conditions of increased relative humidity. Compared to HDF boards, WPC boards are characterized by:

- higher average density and more uniform density profile;
- lower MOR and MOE values. Whereas higher MOR and MOE values are generally shown by PLA-based boards compared to HDPE-based boards;
- generally higher screw holding values. Whereas higher SH values are shown by PLA-based boards with a lignocellulosic particle content of 40 - 50%;
- significantly lower values of swelling and water absorption. However, lower values are shown for HDPE-based boards compared to PLA-based boards.

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Streszczenie: *Kompozyty WPC jako substytut płyt HDF*. W ramach badań wykorzystano przemysłowe płyty HDF oraz wytworzono kompozyty WPC zróżnicowane pod kątem matrycy (PLA i HDPE) oraz udziału napełniacza (40%, 50% i 60%). Oznaczono gęstość i profil gęstości w celu porównania struktury HDF i WPC. Ponadto wytworzone płyty zostały przetestowane pod kątem wytrzymałości (MOR, MOE), utrzymania wkrętów, spęcznienia na grubość oraz nasiąkliwości po moczeniu w wodzie przez 2 i 24 godziny. WPC charakteryzowały się wyższa gęstością niż płyty HDF oraz jednorodnym profilem gęstości. Ponadto kompozyty WPC charakteryzowały się niższymi wartościami MOR i MOE niż płyty HDF. W porównaniu do płyt HDF kompozyty WPC charakteryzowały się wyższymi wartościami zdolności utrzymania wkrętów oraz lepszą odpornością na działanie wilgoci.

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