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Screw holding performance in WPC composites

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Abstract: *Screw holding performance in WPC composites.* In this research effort, the impact of fillers' composition on wood-plastic composites (WPC) made of poly (lactic acid) PLA was tested. The composites varied in filler type (bark, sawdust) and its content in the boards (40, 50, 60%). The composites were manufactured in a two-stage process consisting of extrusion and flat pressing. Analogically prepared HDPE boards were a reference. Composites were tested for density, density profile, and screw-holding ability. Boards based on PLA performed better screw-holding ability than HDPE. The greatest influence was exerted by the share of matrix/filler. An increase in the content of lignocellulosic particles from 40 to 60% (regardless of the type of matrix: PLA or HDPE) generally reduced screw-holding ability. The type of filler (sawdust, bark) was almost 3 times more important in the case of HDPE boards compared to PLA boards.

Keywords: WPC, screw holding, PLA, mechanical properties,

INTRODUCTION

The dynamic development of wood-plastic composites (WPC) in recent years concerns the introduction of new material solutions into their matrix and filler. In both cases, the biodegradability of raw materials is crucial. Traditional WPC composites are produced based on such polymers as: polyethylene PE (decking and construction, consumer goods), polypropene PP (automotive, construction, consumer goods), or polyvinyl chloride PVC (decking & construction) (Partanen and Carus 2019). The composites are easy to process with typical tools and woodworking machines (Zbieć et al. 2010), and they can be joint with the use of typical in wood technology: nails, screws, dowels, gluing (Klysov 2007). The ability to hold screws or nails in wood-polymer composites is comparable or higher than that of solid wood or wood-based materials (Carroll et al. 2001, Falk et al. 2001, Kociszewski et al. 2007, Gozdecki and Kociszewski 2008, Borysiuk et al. 2011).

Nowadays it is also possible to use biodegradable thermoplastics, especially poly (lactic acid) PLA. It can be easily disposed of by composting without negative environmental effects (Markarian 2008). PLA is by far the most widely researched and used biodegradable aliphatic polyester in the history of mankind. Due to its advantages, PLA is a leading biomaterial for many applications in medicine and in the industry replacing conventional petrochemical polymers (Farah et al. 2016).

Wood fibers and wood flour are the main fillers of WPC. The size of applied fillers' particles depends on the intended use of the composites (Kuciel et al. 2010). However, also particles obtained from post-consumer wood materials such as chipboards or MDF can serve as a filler (Gozdecki et al. 2005, 2011, Chaharmahali 2008), as well as recycled fibers (Myers and Clemons 1993, Ashori and Nourbakhsh 2009) or plant materials: bagasse (Fuentes Talavera et al. 2007), bamboo (Lee and Wang 2006), jute (Kuciel et al. 2010), kenafu (Rashdi et al. 2009), hemp (Schrip and Stender 2010), Parthenium shrubs (Chow et al. 2002), maize (Nourbakhsh and Ashori 2009), flax (Markiewicz et al. 2009), rice (Madhoushi et al. 2009), sisal (Espert et al. 2004), rapeseed straw (Markiewicz et al. 2009), grass from the Poaceae family (Li et al. 2009), coconut fiber (Espert et al. 2004). Ground bark is another alternative material for WPC filler (Harper and Eberhardt 2010; Yemele et al. 2010, Safdari et al. 2011, Gozdecki et al. 2009, Gozdecki et al. 2010, Borysiuk et al. 2021). Yemele et al. 2010 reported that WPC composites filled with bark are characterized by lower strength parameters compared to analogous composites filled with wood flour. This corroborates with the findings of other researchers on the mechanical properties of the composites containing bark-filler (Harper and Eberhardt 2010; Safdari et al. 2011, Gozdecki et al. 2009, Gozdecki et al. 2010, Borysiuk et al. 2021).

This study evaluates the impact of fillers' composition applied in PLA matrix on the screw-holding ability of the manufactured WPC composites. An analogous WPC, based on high-density polyethylene (HDPE) matrix were manufactured as a reference. Three levels of fillers' additives (bark or sawdust) at two degrees of comminution were investigated. The composites were manufactured in a two-stage process consisting of extrusion and flat pressing.

METHODS AND MATERIALS

Twenty four variants of WPC composite panels (Table 1, 2) were manufactured 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 Co., Płock, Poland). The composites' fillers contained an addition either of: comminuted pine bark (b) or pine sawdust (s), both supplied from a sawmill. The material was dried to a moisture content of 5% , then mechanically ground and sorted into two fractions:

1. large particles - particles passing through the 2 mm sieve (approx. 10 mesh) and retained by the 0.49 mm sieve (approx. 35 mesh);
2. small particles - particles passing through the 0.49 mm sieve (over 35 mesh).

Table 1. PLA variants' characteristics

Variant	Matrix	Share of Matrix [%]	Share of the filler [%]	
			Small particles (above 35 mesh)	Large particles (10 – 35 mesh)
I	PLA	60		40 s
II	PLA	60		40 b
III	PLA	60	40 b	
IV	PLA	60	40 s	
V	PLA	50		50 s
VI	PLA	50		50 b
VII	PLA	50	50 b	
VIII	PLA	50	50 s	
IX	PLA	40		60 s
X	PLA	40		60 b
XI	PLA	40	60 b	
XII	PLA	40	60 s	

s – sawdust, b – bark

Table 2. HDPE variants' characteristics.

Variant	Matrix	Share of Matrix [%]	Share of the filler [%]	
			Small particles (above 35 mesh)	Large particles (10 – 35 mesh)
XIII	HDPE	60		40 s
XIV	HDPE	60		40 b
XV	HDPE	60	40 b	
XVI	HDPE	60	40 s	
XVII	HDPE	50		50 s
XVIII	HDPE	50		50 b
XIX	HDPE	50	50 b	
XX	HDPE	50	50 s	
XXI	HDPE	40		60 s
XXII	HDPE	40		60 b
XXIII	HDPE	40	60 b	
XXIV	HDPE	40	60 s	

s – sawdust, b – bark

No other additives commonly used in the production of WPC such as compatibilizers were applied in the study.

The composites were manufactured in a two-stage process:

1. WPC granules with the appropriate formulation (Table 1) were produced using the Leistritz Extrusionstechnik GmbH, Nürnberg, Germany extruder (temperatures in individual extruder sections were 170°C - 180°C). The obtained continuous composite web was then ground on a hammer mill;
2. the obtained granulate was used to produce boards with nominal dimensions of 300x300x2.5 mm^3 by flat pressing in a mold, using a single daylight press at a temperature of 200°C and a maximum unit pressing pressure p_{max} = 1.25 MPa (pressure during pressing, along with plasticization of the material, was gradually increased from 0 to p_{max}). Pressing time was 6 min. After hot pressing, the plates were cooled in the mold for 6 min. in a cold press (approx. temp. 20°C).

The manufactured panels were conditioned at ambient temperature and humidity for 7 days under laboratory conditions (20 ± 2°C, 65±5% humidity). The following physical and mechanical properties of the boards 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;
- screw holding (SH) according to EN 320:2011.

Each variant had ten replicates. Statistical analysis of the outcomes was carried out in Statistica version 13 (TIBCO Software Inc., CA, USA). Analysis of variance (ANOVA) was used to test (α=0.05) a significant differences between factors. A comparison of the means was performed by employing Tukey test, with α=0.05.

RESULTS AND DISCUSSION

The tested boards were characterized by densities in the range of 1061 - 1182 kg/m^3 PLA matrix, and 1025 - 1105 kg/m^3 HDPE matrix. The mean density values for individual variants of panels are presented in Table 3. The diversity of density for individual variants within the same matrix (PLA or HDPE) did not exceed 11%. No influence of the size of the filler particles or the type of the filler was noted in this respect. However, it should be noted that the plates made based on PLA with the same proportion, type of filler, and the size of the filler particles were characterized by 1 to 12% higher density, depending on the variant. This is due to the higher density of the PLA matrix compared to the HDPE matrix. Similar relationships were obtained by Andrzejewski et al. (2019) who investigated WPC composites based on PLA and PP.

Table 3. The mean density values for individual variants of panels

Matrix	Share of filler	Bark large particles		Bark small particles		Sawdust large particles		Sawdust small particles	
		ρ	σ	ρ	σ	ρ	σ	ρ	σ
	[%]	[kg/m^3]	[kg/m^3]	[kg/m^3]	[kg/m^3]	[kg/m^3]	[kg/m^3]	[kg/m^3]	[kg/m^3]
PLA	40	1167	47	1171	41	1092	65	1152	56
PLA	50	1159	65	1114	46	1118	44	1146	62
PLA	60	1182	58	1123	51	1061	49	1148	56
HDPE	40	1051	24	1053	26	1025	16	1025	25
HDPE	50	1078	25	1105	27	1035	22	1039	41
HDPE	60	1094	29	1077	38	1026	18	1076	25

ρ – density, σ – standard deviation

All variants of the tested boards were characterized by an uniform density distribution on the cross-section (Figs. 1, 2). The differentiation in the thickness of the individual boards did not exceed 200 kg/m^3, that corroborate the good homogenization of the composite components and the uniform distribution of the filler particles in the polymer matrix. Borysiuk et al. (2019) found that in the case of HDPE boards filled with sawdust, an increase in the filler content reduces the density in the central zone of the board. The authors also concluded that the density and density profile were not affected by the size of the filler particles. This has also been confirmed in the present study.

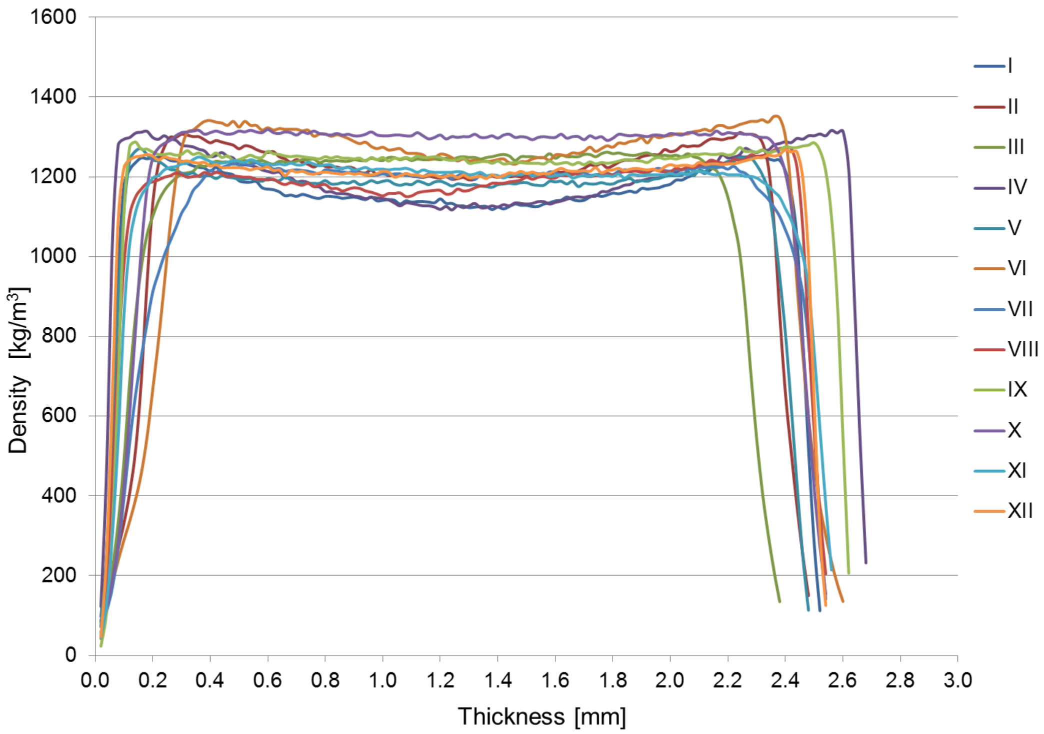

Figure 1. Density profiles of PLA-based plates

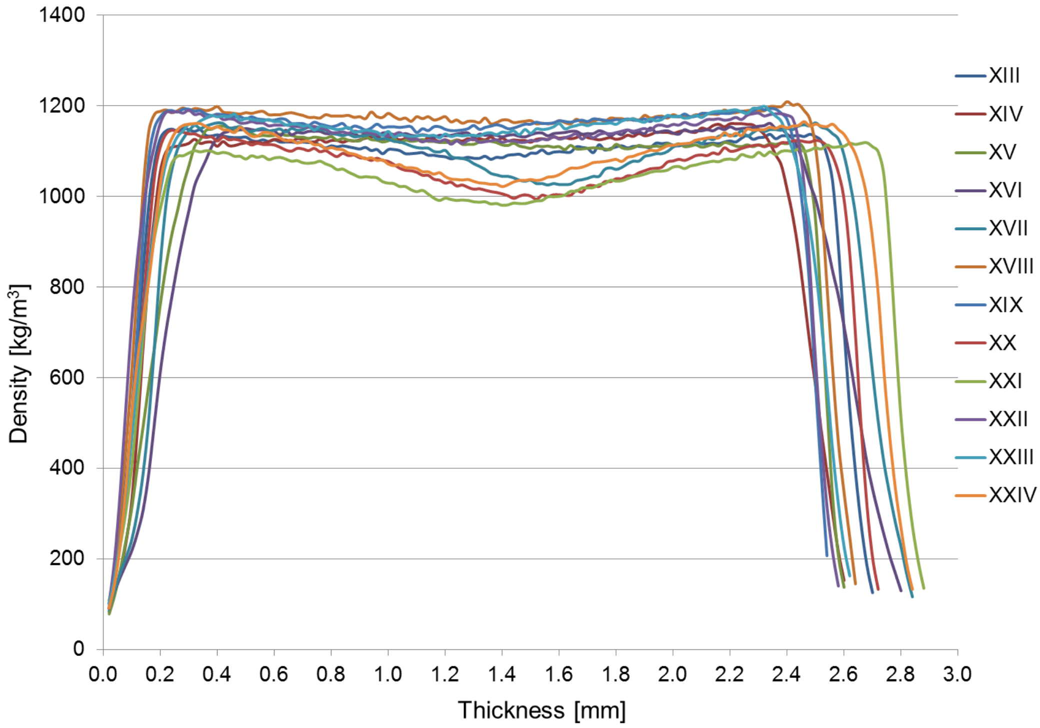

Figure 2. Density profiles of HDPE-based plates

Table 4. Screw-holding capacity outcomes

Mtrix	Share of matrix [%]	Variant	Type of filler	Size of particles	Average screw-holding capacity [N/mm]	Standard deviation [N/mm]
PLA	60	I	Sawdust	Large	284,19 ^{l}	37,68
		IV	Sawdust	Small	279,80 ^{l}	34,55
		II	Bark	Large	219,55 ^{ij}	23,23
		III	Bark	Small	228,36 ^{jk}	26,74
	50	V	Sawdust	Large	183,49 ^{efg}	24,03
		VIII	Sawdust	Small	254,89 ^{kl}	20,63
		VI	Bark	Large	164,96 ^{cdef}	23,02
		VII	Bark	Small	99,68 ^{a}	14,10
	40	IX	Sawdust	Large	175,81^{defg}	20,80
		XII	Sawdust	Small	112,98 ^{ab}	16,32
		X	Bark	Large	215,35 ^{hij}	28,81
		XI	Bark	Small	96,63 ^{a}	12,84
HDPE	60	XIII	Sawdust	Large	186,29 ^{fgh}	16,07
		XVI	Sawdust	Small	190,15 ^{fghi}	11,61
		XIV	Bark	Large	151,72 ^{cd}	7,95
		XV	Bark	Small	154,29 ^{cde}	8,75
	50	XVII	Sawdust	Large	164,77 ^{cdef}	10,14
		XX	Sawdust	Small	199,20 ^{ghij}	22,72
		XVIII	Bark	Large	145,71 ^{cd}	7,61
		XIX	Bark	Small	150,07 ^{cd}	8,87
	40	XXI	Sawdust	Large	137,38 ^{bc}	10,55
		XXIV	Sawdust	Small	139,14 ^{bc}	13,71
		XXII	Bark	Large	98,90 ^{a}	2,95
		XXIII	Bark	Small	136,55 ^{bc}	8,54

a,b,……,k,l – homogenous groups

Table 4 presents the outcomes of the screw-holding test. Regardless of the filler used, it can generally be stated that the boards made based on PLA are characterized by a higher holding capacity of the screws compared to HDPE boards. This is related to the higher stiffness of PLA compared to polyolefins (Gurunathan et al. 2015). In turn, the increase in the content of filler particles (decrease in the share of the thermoplastic matrix) in most variants resulted in a decrease in the holding capacity of the screws. This is especially visible in the case of PLA-based plates. A decrease in the SH value along with the increase in the content of wood flour was also noted by Gozdecki and Kociszewski (2008) when examining composites based on PP. In turn, Falk et al. (2001) for LDPE and PP composites and wood flour found that the increase in the lignocellulosic filler content did not affect the SH values. When analyzing the obtained test results (Table 4), it can also be stated that higher values of the screw holding capacity are generally achieved by variants of composites filled with sawdust compared to analogous composites filled with bark. This may be due to the greater susceptibility of the bark particles to cracking, and thus lowering the strength of the composite. These cracks may appear at the stage of producing composites during the transfer and division of the raw material in the extruder (Hietala et al. 2011).

When considering all four variables i.e.: the type of matrix, the share of matrix / filler, and the type of filler and its size, it may be concluded that they have a significant effect on the SH values of composites (Table 5). However, the greatest impact indicated the share of matrix / filler (X = 28.99%). Similar dependencies were obtained by Borysiuk et al. (2021). The remaining factors: the type of matrix and the type of filler had the percentage of 12.17% and 11.38%, respectively. The total percentage of contribution of these three factors (matrix type, matrix / filler share and filler type) was 52.54%, and corroborates their significant nature. It is also worth adding that both: the effect of filler size and the interaction between individual factors, although significant, were less than the effect of factors not considered in this study (error = 11.08%).

Table 5. ANOVA for selected factors affecting SH of manufactured composites

	SS	Degree	MS	F	p	X[%]
Matrix (M)	87537	1	87537	233,97	0,0000	12.17
Thermoplastic share (TS)	208620	2	104310	278,80	0,0000	28.99
Fillers type (FT)	81860	1	81860	218,79	0,0000	11.38
Particles size (PS)	3067	1	3067	8,20	0,0046	0.43
M x TS	58450	2	29225	78,11	0,0000	8.12
M x FT	3105	1	3105	8,30	0,0044	0.43
TSx FT	33438	2	16719	44,69	0,0000	4.65
M x PS	26858	1	26858	71,79	0,0000	3.73
TS x PS	24350	2	12175	32,54	0,0000	3.38
FT x PS	12563	1	12563	33,58	0,0000	1.75
M x TS x FT	18244	2	9122	24,38	0,0000	2.54
M x TS x PS	34393	2	17197	45,96	0,0000	4.78
M x FT x PS	13898	1	13898	37,15	0,0000	1.93
TS x FT x PS	22561	2	11281	30,15	0,0000	3.14
M x TS x FT x PS	10776	2	5388	14,40	0,0000	1.50
Error	79692	213	374			11.08

p – probability of error, X – percentage of contribution

Analyzing independently composite boards based on PLA and HDPE, it can be seen that in both cases, the greatest impact on the ability to hold screws had the share of matrix X=42.04% and 43.13%, respectively (Tables 6 and 7). On the other hand, the type of filler is almost 3 times more important in the case of HDPE-based boards (X=27.08%) compared to

PLA-based boards (X=10.94%). This differentiation is probably related to the aforementioned higher PLA stiffness. It is worth adding here that also in the case of independent consideration of PLA and HDPE boards, both the influence of the filler size and the interaction between individual factors were less than the influence of factors not included in this study (error 12.28% and 15.12%, respectively).

Table 6. ANOVA for selected factors affecting SH of manufactured PLA composites

	SS	Degree	MS	F	p	X
Thermoplastic share (TS)	221330	2	110665	179.678	0.0000	42.04
Fillers type (FT)	57637	1	57637	93.581	0.0000	10.94
Particles size (PS)	23713	1	23713	38.501	0.0000	4.50
TS x FT	49529	2	24764	40.208	0.0000	9.41
TS x PS	55854	2	27927	45.343	0.0000	10.61
FT x PS	26087	1	26087	42.355	0.0000	4.95
TS x FT x PS	27769	2	13885	22.543	0.0000	5.27
Error	64670	105	616			12.28

p – probability of error, X – percentage of contribution

Table 7. ANOVA for selected factors affecting SH of manufactured HDPE composites

	SS	Degree	MS	F	p	X
Thermoplastic share (TS)	42848	2	21424	154,03	0,0000	43.13
Fillers type (FT)	26907	1	26907	193,45	0,0000	27.08
Particles size (PS)	5969	1	5969	42,91	0,0000	6.01
TS x FT	1335	2	668	4,80	0,0101	1.34
TS x PS	17	1	17	0,12	0,7265	0.02
FT x PS	1779	2	890	6,40	0,0024	1.79
TS x FT x PS	5468	2	2734	19,66	0,0000	5.50
Error	15022	108	139			15.12

p – probability of error, X – percentage of contribution

CONCLUSIONS

1. Composite boards based on PLA had generally greater ability to hold screws compared to analogous composite boards based on HDPE.
2. The share of matrix/ filler had largest influence on the screw-holding ability regardless of the type of matrix (PLA or HDPE).
3. An increase in the content of lignocellulosic particles from 40 to 60% (regardless of the type of matrix PLA or HDPE) generally reduces the screw-holding ability.
4. Boards filled with sawdust particles had a higher holding capacity compared to the boards filled with bark particles regardless of the matrix type (PLA or HDPE).
5. The type of filler (sawdust, bark) was almost 3 times more important in the case of HDPE-based boards than in PLA-based boards.
6. Regardless of the matrix type (PLA, HDPE) and the filler (sawdust, bark), composite panels had a similar average density and the density profiles.

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Streszczenie: *Zdolność utrzymania wkrętów w kompozytach WPC.* W ramach niniejszych badań określono wpływ dodatku napełniacza (kory lub trocin) do matrycy z PLA na zdolność utrzymania wkrętów przez kompozyty WPC. W celu porównania wykonano analogiczne kompozyty WPC na bazie matrycy z polietylenu (HDPE). Zastosowano 3 poziomy napełnienia kompozytów przy dwóch rodzajach oraz dwóch stopniach rozdrobnienia napełniaczy. Kompozyty wytwarzano dwuetapowo metodą wytłaczania i prasowania płaskiego. Dla wytworzonych kompozytów zbadano gęstość, profil gęstości oraz zdolność utrzymania wkrętów. Badania wykazały, że płyty kompozytowe na bazie PLA charakteryzują się na ogół większą zdolnością utrzymywania wkrętów w porównaniu do analogicznych płyt kompozytowych na bazie HDPE. Ponadto największy wpływ na zdolność utrzymywania wkrętów wykazuje udział matrycy/napełniacz. Przy czym wzrost zawartości cząstek lignocelulozowych z 40 do 60% (niezależnie od rodzaju matrycy: PLA czy HDPE) wpływa na ogół na spadek zdolności utrzymywania wkrętów. Rodzaj wypełniacza (trociny, kora) odgrywa prawie 3-krotnie większe znaczenie w przypadku płyt wytworzonych na bazie HDPE w porównaniu do płyt wytworzonych na bazie PLA

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