MECHANICAL PROPERTIES OF WOOD–POLYPROPYLENE COMPOSITES WITH INDUSTRIAL WOOD PARTICLES OF DIFFERENT SIZES

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Abstract. Industrial wood particles used for manufacturing three-layer particleboards were used to prepare wood–polypropylene composites by an injection molding process. The effect of particle size (0.25-0.5, 0.5-1, 1-2, and 2-4 mm) on mechanical properties of composites was investigated. Additionally, the effect of cross-section size of composite pieces (4×10, 6×15, and 8×20 mm^2) was studied. Both particle size and specimen cross-section area significantly influenced these properties. Tensile and mechanical properties as well as impact strength increased with increasing particle size from 0.25-2 mm and then slightly decreased. Flexural and impact strength decreased with increasing cross-section size, whereas variation of tensile modulus and strength and of flexural modulus with increasing cross-section size was different for composites with different particle sizes.

Keywords: Industrial wood particle, injection, mechanical properties, particle size, polypropylene, wood–plastic composite.

INTRODUCTION

Mechanical properties of wood–plastic composites (WPCs) depend on many factors, the effects of which have been the subject of many studies. Mainly, the effects of wood species, wood content, and coupling agent content have been investigated, whereas there are relatively few studies on the effects of wood particle size.

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Typical WPCs are made using small wood particles (WP) or short wood fibers (WF). The effect of the size of small WP, smaller than 1 mm, on WPC mechanical properties has been mainly evaluated for wood–polypropylene (PP) composites with 40 wt% WP content and without a coupling agent (Zaini et al 1996; Stark and Berger 1997; Stark and Rowlands 2003; Khalil et al 2006; Salemane and Luyt 2006). Stark and Berger (1997) and Stark and Rowlands (2003) found that tensile and flexural properties increased slightly with increasing WP size from 0.064-0.215 mm and then decreased when WP size reached 0.513 mm. Zaini et al (1996) reached a similar conclusion for WPC with WP size from 0.063-0.250 mm. However, increase in mechanical properties caused by increasing WP size was greater. Salemane and Luyt (2006) concluded that increasing WP size from 0.038-0.600 mm improved tensile modulus and decreased tensile strength. Khalil et al (2006) studied properties of WPC with WP size ranging from 0.100-0.300 mm and found that increasing WP size considerably decreased tensile properties and flexural modulus and slightly increased flexural strength.

The effect of small WP size on mechanical properties was also investigated for WPC with other thermoplastics. Takatani et al (2000) studied flexural strength of WPC with softwood flour and steam-exploded beech flour using two sizes of WP: 0.125 and 0.841 mm. Thermoplastic components were polyvinyl chloride and polystyrene. They reported that WP size of 0.125 mm gave greater WPC strength than the size of 0.841 mm when softwood flour was the wood component. WPC strength was less when a mix of softwood and steam-exploded beech flour was the wood component. Bouafif et al (2009) studied properties of WPC consisting of wood flour and high-density polyethylene (HDPE). They observed that tensile and flexural properties increased with increasing WP size from 0.150-0.850 mm.

The effect of the length of short WF, shorter than 4 mm, on mechanical properties of wood–PP composites was the subject of several studies (Liew et al 2000; Lee et al 2001; Kumari et al 2007; Pan et al 2009). Kumari et al (2007) concluded that flexural properties of WPC with a coupling agent and 80 wt% WF content increased with increasing WF length from 0.120-0.300 mm and decreased with increasing WF length to 0.900 mm. Liew et al (2000) found that tensile and flexural strength of WPC with 40 wt% WF content and without a coupling agent increased when WF length increased from 0.5-2.0 mm. Lee et al (2001) investigated similar WPCs and observed a considerably greater increase in mechanical properties with increasing WF length from 1.7-3.2 mm. Next, Pan et al (2009) concluded that these properties of WPC with a coupling agent and 20 wt% WF content increased very slightly when WF length increased from 0.5-2.2 mm.

The effect of the length of short WF on mechanical performance of wood–HDPE composites also has been studied. Migneault et al (2008) found that tensile and flexural properties of WPC with 40 wt% wood content and without a coupling agent increased when WF length increased from 0.196-0.481 mm. Cui et al (2008) reached the reverse conclusion for flexural properties of WPC made with a coupling agent. Flexural properties decreased with increasing WF length from 0.075-0.900 mm.

Results of presented studies on the effect of small WP size and short WF length on WPC mechanical properties vary quite greatly. Some studies have shown that this effect was considerable, whereas others have presented a limited effect. For most tested WPC, increasing WP size and WF length increased mechanical properties, but in several cases, there was a reverse tendency. These differences in study results are difficult to interpret. They were caused by many factors such as wood species, thermoplastic type, wood content, coupling agent type and content, and processing method. One can conclude that the effect of WP size and WF length on WPC mechanical properties is not fully understood.

A comparison of WPC made of small WP and short WF (Zaini et al 1996; Stark 1999; Liew et al 2000; Takatani et al 2000; Lee et al 2001; Stark and Rowlands 2003; Khalil et al 2006; Salemane and Luyt 2006; Kumari et al 2007; Cui et al 2008; Migneault et al 2008; Bouafif et al 2009; Pan et al 2009) shows that WF led to better WPC mechanical properties than WP. Commercial wood flour has WPs with low length to diameter ratio ranging from 3.35-4.53, whereas for WF, this ratio is many times higher. The higher length to diameter ratio enhances stress transfer from the polymer matrix to the WF and finally improves WPC mechanical properties.

Large-sized WPs, larger than 1 mm (18 mesh), are not used for manufacturing WPC. Particles that are too large make it difficult to process WPC by an injection and extrusion molding method. Chen et al (2006) studied mechanical properties of WPC made of large-sized WP and HDPE using a compression molding process. They concluded that WPC flexural properties increased with increasing WP size from 0.59 to more than 1.18 mm. Bledzki and Faruk (2003) compared mechanical properties of wood–PP composites made with large-sized industrial WP with those made with typical wood flour using an injection molding process. They found that mechanical properties of these WPC were almost the same. Industrial WPs also were applied by Gozdecki et al (2006) to prepare the wood–PP composite using an injection molding method. They compared tensile properties of WPC with WP used in manufacturing face layers of particleboard and with standard wood flour and observed that using industrial WP improved properties.

Rapid growth in demand for WPC in recent years and their new application make it necessary to investigate new WPC for appropriate properties. WPC with large-sized WP instead of wood flour and short WF can be of particular usefulness. In this study, we used industrial WP, usually used for manufacturing both face and core layers of particleboard, to make wood–PP composites using an injection molding method. The objective of this study was to investigate the effect of WP size on mechanical properties of these composites. Using large-sized WP makes the WPC more heterogeneous; therefore we decided to also consider cross-section size of injection-molded pieces.

MATERIALS AND METHODS

Polypropylene

The PP used in this study was homopolymer Moplen HP648T (Basell Orlen Polyolefins, Plock, Poland). Its density was 900 kg/cm^3, and its melt flow index was 53 g per 10 min (230°C/2.16 kg).

Industrial Wood Particles

Two kinds of softwood particles used for manufacturing three-layer particleboards, fine particles for face layers and coarse particles for core layer, were supplied by Kronospan Szczecinek (Poland). Fraction analysis of these particles is shown in Table 1.

Experimental Design

To study the effect of WP size on WPC mechanical properties, four WP sizes were assumed: 1) very small (S1), 0.25-0.5 mm; 2) small (S2), 0.5-1 mm; 3) large (L1), 1-2 mm; and 4) very large (L2), 2-4 mm. For determining the effect of cross-section size of injection-molded products, three cross-section areas were planed: 1) 4 × 10 mm^2; 2) 6 × 15 mm^2; and 3) 8 × 20 mm^2. A 4 × 3 completely factorial design of experiments

Table 1. Fraction analysis of industrial wood particles.

Fine particles		Coarse particles	
Screen hole size range (mm)	Content (%)	Screen hole size range (mm)	Content (%)
<0.212	11.5	<0.5	1.9
0.212-03	9.2	0.5-1.0	8.5
0.3-0.4	15.5	1.0-1.4	11.3
0.4-0.6	20.9	1.4-2.0	28.9
0.6-1.0	39.5	2.0-4.0	42.9
1.0-1.25	3.2	4.0-6.3	5.8
>1.25	0.2	>6.3	0.7

was assumed using only one WP/PP ratio of 40/60%. To compare mechanical properties of WPC with industrial WP and typical wood flour, the experimental design was extended to include WPC with softwood flour (Lignocel® BK 40/90; J. Rettenmaier & Söhne GmbH, Rosenberg, Germany).

Wood Particle Characteristics

To obtain four sizes, industrial WPs were screened by an analytical sieve shaker using sieves of 5, 10, 18, 35, and 60 mesh. Screened particles are shown in Fig 1. Dimensions of 200 randomly selected particles of each size were measured using an optical microscope with a measuring scale. Magnification of 30× for S1 and S2 particles and 10× for L1 and L2 particles were used. Length to thickness and width to thickness ratios were calculated to obtain geometric characteristics of WP. WP bulk density was also determined. Mean values of these parameters both for industrial WP and BK 40/90 wood flour are listed in Table 2.

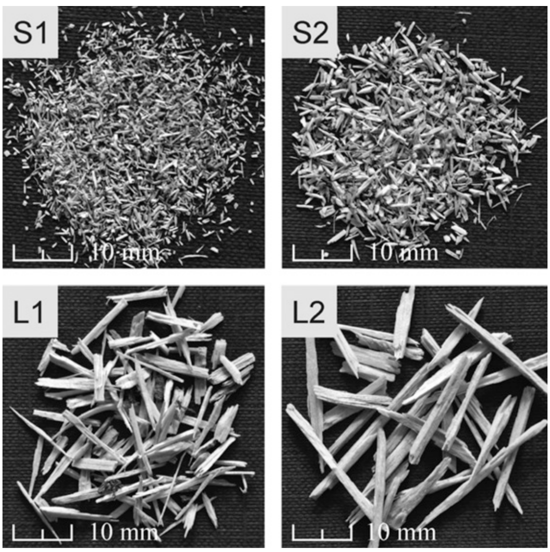

Figure 1. Screened wood particles of S1, S2, L1, and L2 sizes (very small, small, large, and very large, respectively).

Processing

All WPs were dried at 80°C in an air-circulation oven for 24 h before the mixing process to achieve less than 3% MC. Next, WP was mixed with PP at 40% by weight. Test specimens were made by injection molding using an AH-80 screw injection molding machine. The temperature profile was 120, 180, and 180°C at feed, Zone 1, and Zone 2, respectively. Injection pressure time and hold pressure time were 3 and 6 s, respectively. To minimize mechanical degradation of WP during molding, the diameter of the injection die was enlarged to 4.5 mm and diameter of the sprue bush to 8 mm. Cross-sections of the runner and the gate were 10 × 10 and 6 × 6 mm^2, respectively.

Specimens of three cross-section sizes were made. Dimensions of those of 4 × 10 mm^2 cross-sections were according to EN ISO 527 (EN ISO 1996), and dimensions of those of 6 × 15 and 8 × 20 mm^2 cross-sections were adequately larger. After processing, specimens were stored in controlled conditions (50% RH and 20°C) for 2 wk prior to testing.

Mechanical Property Testing

Mechanical properties of tested WPC were evaluated in relation to tensile, flexural, and impact properties. Tensile and flexural tests were performed according to EN ISO 527 (EN ISO 1996) and EN ISO 178 (EN ISO 2005), respectively, using an Instron (Norwood, MA) 3367 machine. Span length in the flexural test was 16 times the thickness of the specimen. Crosshead speed was 2 mm/min. Unnotched Charpy impact

Table 2. Mean values of length, length/thickness and width/thickness ratios, and bulk density of WP.[a]

	Length (mm)	Length/thickness	Width/thickness	Bulk density (kg/cm^3)
S1	1.9 (0.8)	14.9 (3.2)	2.4 (0.7)	201
S2	3.9 (1.4)	16.3 (4.1)	2.5 (0.9)	192
L1	12.2 (6.0)	20.2 (6.1)	2.6 (1.2)	162
L2	20.2 (6.9)	21.4 (6.3)	2.8 (1.1)	150
BK	1.5 (0.4)	12.8 (5.6)	3.4 (1.4)	205

[a] Standard deviations in parentheses.
WP, wood particles.

strength tests were conducted according to EN ISO 179 (EN ISO 2000). Ten replicates were run for each test. All tests were performed at room temperature (20°C) and at constant RH (50%).

RESULTS AND DISCUSSION

Figures 2-6 show mean values of tensile modulus (Fig 2) and strength (Fig 3), flexural modulus (Fig 4), and strength (Fig 5), and unnotched impact strength (Fig 6) of tested WPC with industrial WP. Error bars represent one standard deviation based on 10 specimens. Two-way analysis of variance was conducted to determine significance of the effects of WP size and cross-section size on WPC mechanical properties (Table 3). Results of this analysis showed that all mechanical properties vary significantly with WP size and specimen cross-section size. Interaction between these two variables is significant only for tensile and flexural strength.

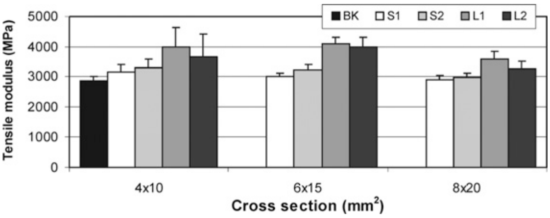

Figure 2. Tensile modulus of tested wood–plastic composites (S1, very small; S2, small; L1, large; L2, very large).

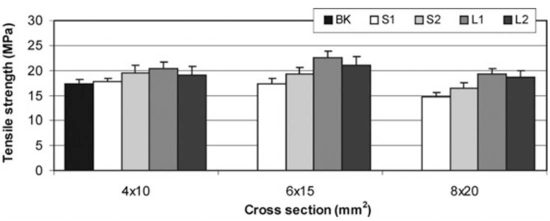

Figure 3. Tensile strength of tested wood–plastic composites (S1, very small; S2, small; L1, large; L2, very large).

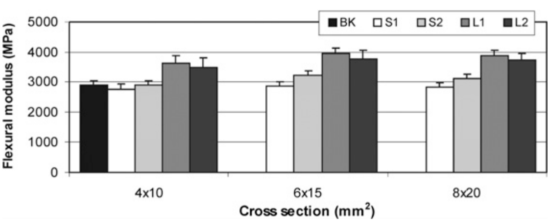

Figure 4. Flexural modulus of tested wood–plastic composites (S1, very small; S2, small; L1, large; L2, very large).

Effect of Wood Particle Size

Specimens of different cross-section size but with the same WP size were included in one group. Mean values of mechanical properties for these groups are presented in Table 4. Tukey's test was applied to determine statistical significance among mean values of mechanical properties of WPC with different WP sizes. Values with the same letter for each property were not significantly different at the 5% level.

In general, increasing WP size improved WPC mechanical properties. Tensile and flexural properties increased with increasing WP size from S1 to L1. Mechanical properties of WPC

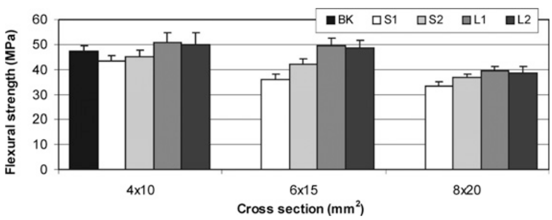

Figure 5. Flexural strength of tested wood–plastic composites (S1, very small; S2, small; L1, large; L2, very large).

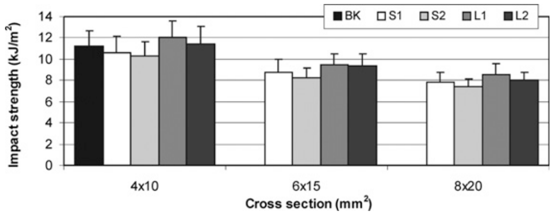

Figure 6. Impact strength of tested wood–plastic composites (S1, very small; S2, small; L1, large; L2, very large).

Table 3. Two-way analysis of variance test on effects of WP size and cross-section size on WPC mechanical properties (p values).

Variable	Tensile modulus	Tensile strength	Flexural modulus	Flexural strength	Impact strength
WP size	<0.0001*	<0.0001*	<0.0001*	<0.0001*	0.0002*
Cross-section size	<0.0001*	<0.0001*	<0.0001*	<0.0001*	<0.0001*
WP size × cross-section size	<0.2549 NS	0.0014*	0.0856 NS	<0.0001*	0.9141 NS

* Denotes significance at 0.01.
NS, not significant at 0.05; WP, wood particles; WPC, wood–plastic composites.

Table 4. Effect of WP size on WPC mechanical properties.[a]

Wood particle size	Tensile modulus (MPa)	Tensile strength (MPa)	Flexural modulus (MPa)	Flexural strength (MPa)	Impact strength (kJ/m^2)
S1	2998[a] (209)	16.6[a] (1.7)	2810[a] (155)	37.6[a] (4.8)	9.08[ab] (1.7)
S2	3164[a] (252)	18.4[b] (2.0)	3070[b] (207)	41.3[b] (4.0)	8.67[a] (1.6)
L1	3839[b] (496)	20.7[c] (1.8)	3814[c] (255)	46.6[c] (6.0)	10.01[b] (1.9)
L2	3626[b] (570)	19.6[bc] (1.9)	3650[d] (320)	45.8[c] (6.1)	9.60[ab] (1.9)

[a] Mean values with the same letter for each property were not significantly different at the 5% level. Standard deviations are in parentheses.
WP, wood particles; WPC, wood–plastic composites; S1, very small; S2, small; L1, large; L2, very large.

with L1 particles were greater by 28, 25, 35, and 24% than those of WPC with S1 particles for tensile modulus, tensile strength, flexural modulus, and flexural strength, respectively. This tendency was a result of WP geometry. According to the theory of mechanics of fiber-reinforced composite material, their mechanical properties depend among other things on particle size and aspect ratio. WP with higher aspect ratios improved WPC properties (Zaini et al 1996; Stark and Rowlands 2003; Migneault et al 2008). The influence of WP size was inconsistent. Zaini et al (1996), Chen et al (2006), and Bouafif et al (2009) observed an increase in WPC mechanical properties with increasing WP size, whereas Stark and Berger (1997) showed the opposite tendency for WPC with WP larger than 0.25 mm. Khalil et al (2006) also found that increasing WP size decreased in mechanical properties. In this study, larger WP had not only longer length, but also higher aspect ratio (length to thickness ratio) (Table 2). This confirms that the effect of aspect ratio on mechanical properties of WPC was more significant than the effect of particle size.

Increase in WP size from L1 to L2 resulted in a less than 6% decrease in WPC tensile and flexural properties. This was probably caused by the fact that large WPs were breaking during the mixing process.

Effect of WP size on WPC impact strength was different. The energy needed to cause dynamic failure of WPC specimens decreased when WP size increased from S1 to S2, increased when WP size increased from S2 to L1, and again decreased when WP size increased from L1 to L2. The relative difference between maximum value (WPC with L1 particles) and minimum value (WPC with S2 particles) of impact strength was 15%.

Effect of Cross-Section Size

The effect of specimen cross-section size on WPC tensile properties was different for WPC with smaller (S1 and S2) and larger (L1 and L2) WP (Table 4). For WPCs with smaller WP, these properties decreased gradually with increasing cross-section size. Tensile modulus and strength determined on specimens of 8 × 20-mm^2 cross-section decreased an average of 13% compared with those determined on specimens of 4 × 10-mm^2 cross-section. WPC with larger WP showed a different trend. Tensile properties increased, an average of 8%, when cross-section size increased from 4 × 10 to 6 × 15 mm^2 and decreased, an average of 14%, when cross-section size increased to 8 × 20 mm^2.

WPC flexural modulus increased, an average of 8%, with increasing cross-section size from 4 × 10 to 6 × 15 mm^2 and next decreased, an average of 2%, with increasing cross-section size to 8 × 20 mm^2. WPC flexural strength varied otherwise. It decreased gradually when cross-section size increased from 4 × 10 to 8 × 20 mm^2. Its value determined on specimens of 8 × 20 mm^2 was an average of 22% lower than the value determined on specimens of 4 × 10 mm^2. Increase in specimen cross-section size also decreased WPC impact strength. This strength determined on 8 × 20-mm^2 specimens was on average smaller by 28% than that determined on 4 × 10-mm^2 specimens.

Results for determined WPC mechanical properties were influenced by both WP size and cross-section size. Standard deviations were higher when WP was larger. Their increase with increasing WP size was highest for results determined from specimens with the smallest cross-section. Standard deviations were lower for results determined from specimens with larger cross-sections. The decrease in standard deviations with increasing cross-section size was greater for WPC with larger WP. Therefore, the smaller the WP size and the larger the cross-section size, the lower the standard deviation. Taking this into account, it is preferable to use specimens with a cross-section larger than the standard of 4 × 10 mm^2 to determine mechanical properties of WPC with larger WP, especially when determining flexural and impact strength because, for these properties, lower values were achieved on specimens with larger cross-section.

Comparison of Wood–Plastic Composites with Industrial Wood Particles and Commercial Wood Flour

The performance of WPC with industrial WP and WPC with commercial wood flour (BK) was compared. For that purpose, WPCs containing the smallest WP (S1) and BK particles were compared (particle dimensions were comparable) (Table 2). Mean values of mechanical properties of WPC with BK particles are presented in Figs 2-6. Tensile properties of WPCs with industrial WP were higher than those of WPC with BK, but the relative difference did not exceed 10%, and only for tensile modulus was it statistically significant. Flexural properties and impact strength of WPC with industrial WP were an average of 6% lower than those of WPC with BK, and only for flexural strength was the difference between mean values statistically significant.

CONCLUSIONS

Industrial WP used for manufacturing three-layer particleboards was found to be a good material for making composites with PP by an injection molding method. These WPCs had good mechanical properties, which depended on WP size and the cross-section area of the injection-molded pieces. Larger WP, used for manufacturing the core layer of particleboards, contributed to a better performance from WPC. Mechanical property values determined on specimens with larger cross-section were in general lower. Standard deviations of WPC mechanical properties were higher when WPs were larger and were lower when cross-section size was larger. Using specimens with a larger cross-section than the standard of 4 × 10 mm^2 is preferable to determine mechanical properties of WPC with larger WP, especially when determining flexural strength and impact strength.

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