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Effect of wood particle size on mechanical properties of industrial wood particle-polyethylene composites

Summary — Industrial wood particles used for manufacturing three-layers particleboards were employed to prepare wood/PE-LD composites by an injection molding process. The effect of particle size (sieve analysis 0.25—0.5, 0.5—1, 1—2, and 2—4 mm) and of specimen cross-section size (40, 90 and 160 mm^2) on the mechanical properties was studied. Both these factors significantly influenced studied properties. The tensile, flexural and impact strengths properties in general increased with increasing particle size while with increasing of specimen cross-section the tensile and flexural moduli increased, and the tensile, flexural and impact strengths decreased.
Keywords: industrial wood particle, low-density polyethylene, composites, injection, molding, wood particle size, mechanical properties.

WPŁYW WYMIARÓW CZĄSTEK DRZEWNYCH NA WŁAŚCIWOŚCI MECHANICZNE KOMPOZYTÓW POLIETYLEN/PRZEMYSŁOWE WIÓRY DRZEWNE

Streszczenie — Przemysłowe wióry drzewne stosowane do produkcji trójwarstwowych płyt wiórowych zostały wykorzystane do wytworzenia metodą wtryskiwania kompozytu PE-LD/drewno (rys. 1, tabela 1). Wióry te charakteryzowały się dużą "smukłością". Mianowicie, stosunek ich długości do grubości (ang. *aspect ratio*) wynosił ok. 15 w przypadku drobnych wiórów używanych na warstwy zewnętrzne płyt wiórowych i ok. 20 dla dużych wiórów stosowanych na warstwę wewnętrzną takich płyt (tabela 2). Udział masowy składnika drzewnego wynosił 40 %. Zbadano wpływ wielkości wiórów (0,25—0,5, 0,5—1, 1—2 i 2—4 mm wg analizy sitowej), a także wpływ wielkości przekroju poprzecznego (40, 90 i 160 mm^2) wtryskiwanych elementów (próbek wiosełkowych) na właściwości mechaniczne kompozytu. Stwierdzono, że obydwa te czynniki wywierają istotny wpływ na wytrzymałości i moduły kompozytu przy rozciąganiu i zginaniu statycznym oraz na jego udarność (tabela 3, rys. 2 i 3). Kompozyt z dużymi wiórami charakteryzuje się mianowicie lepszymi właściwościami niż kompozyt z drobnymi wiórami. Jest to spowodowane faktem, iż duże, bardziej smukłe wióry lepiej orientują się w kierunku osi próbki i efektywniej przejmują siły wewnętrzne z matrycy polimerowej. Moduły sprężystości przy rozciąganiu i zginaniu wyznaczone z zastosowaniem próbek o większych przekrojach są większe, natomiast wytrzymałości na rozciąganie i zginanie oraz udarność są tym mniejsze, im większy jest przekrój próbki. Rozrzuty wyników zawężają się wraz ze zmniejszaniem wymiarów wiórów i zwiększaniem przekroju próbki. Do wyznaczania właściwości mechanicznych kompozytów z dużymi cząstkami drzewnymi wskazane byłoby więc stosowanie próbek o przekroju większym, niż zalecany przez normy przekrój 40 mm^2.
Słowa kluczowe: przemysłowe wióry drzewne, polietylen małej gęstości, wtryskiwanie, kompozyty, wymiary cząstek drzewnych, właściwości mechaniczne.

Mechanical properties of wood-plastic composites depend on many factors. Among the most important ones is the wood particle size. The effect of this factor was mainly evaluated for typical wood particles composites (WPC) made using small wood particles (wood flour) or short wood fibers. Generally WPC with PP [1—6] and PE-HD [7—9] were studied. The results of these studies are divergent. Some studies [1, 2, 4, 6—9] have shown that the effect of wood particle size is considerable, whereas others [3, 5] have presented a limited effect. For most tested WPC increasing wood particle size results in an improvement (increasing) of the mechanical properties [1, 2, 5—7, 9], but in some cases there is a reverse ten-

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dency [3, 4, 8]. The differences in the results of these studies are difficult to interpret. They are due to many factors, mainly such as a thermoplastic type, wood content, wood particle geometry, coupling agent type and content, and processing method. It can be concluded that the effect of wood particle size on the WPC mechanical properties is not sufficiently explained.

There have been few studies on the mechanical properties of WPC with PE-LD as the matrix [10—13]. They mainly refer to the effect of a wood or natural fiber content. Only Steller and Meissner [10] have evaluated the effect of cellulose particle size, concluding that a longer cotton fiber improves the WPC tensile strength.

Large-sized wood particles are seldom used as the filler of WPC, especially in the production of WPC by injection molding. However, industrial wood particles with great length and a high length-to-thickness ratio were found to be useful for producing wood-PP composites [14—16]. Using these particles improves the WPC mechanical properties, compared to typical WPC made with wood flour.

The increasingly wide use of WPC requires manufacturing these products with specific properties. Such can be WPC with large-sized wood particles. In this study industrial wood particles used for manufacturing the face and core layers of particleboard were employed to make the wood/PE-LD composites by an injection molding method. The aim of the study was to assess the effect of particle size on the mechanical properties of these composites. The use of large-sized particles makes the WPC more heterogeneous, therefore it was decided to consider also a size of a cross-section of injection molded pieces.

EXPERIMENTAL

Materials

— The PE-LD used in this study was a homopolymer Malen E FABS, 23-DO22 [supplied by Basell Orlen Polyolefins (Poland)] with density 0.92 g/cm^3 and melt flow rate 2 g/10 min (230 °C/2,16 kg).

— Industrial soft wood particles (WP) used for manufacturing three-layer particleboards — fine particles for face layers and coarse particles for a core layer — were employed as a raw wood material. They were supplied by Kronospan Szczecinek (Poland). The results of their fraction analysis are shown in Table 1. The particles were screened by an analytical sieve shaker LAB-11-200/UP using the sieves of 5, 10, 18, 35 and 60 mesh to obtain four particle sizes: (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. The 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 was used. Length-to-thickness and width-to-thickness ratios were calculated to obtain particle geometric characteristics. The particle bulk density was also determined, according to CEN/TS 15103. Mean values of these parameters are listed in Table 2.

T a b l e 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—0.3	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

T a b l e 2. Length, length/thickness and width/thickness ratios, and bulk density of wood particles

Symbol	Length*) mm		Length/ thickness*) (aspect ratio)		Width/ thickness*)		Bulk density g/cm^3
S1	1.9	(0.8)	14.9	(3.2)	2.4	(0.7)	0.201
S2	3.9	(1.4)	16.3	(4.1)	2.5	(0.9)	0.192
L1	12.2	(6.0)	20.2	(6.1)	2.6	(1.2)	0.162
L2	20.2	(6.9)	21.4	(6.3)	2.8	(1.1)	0.150

*) Standard deviations in parentheses.

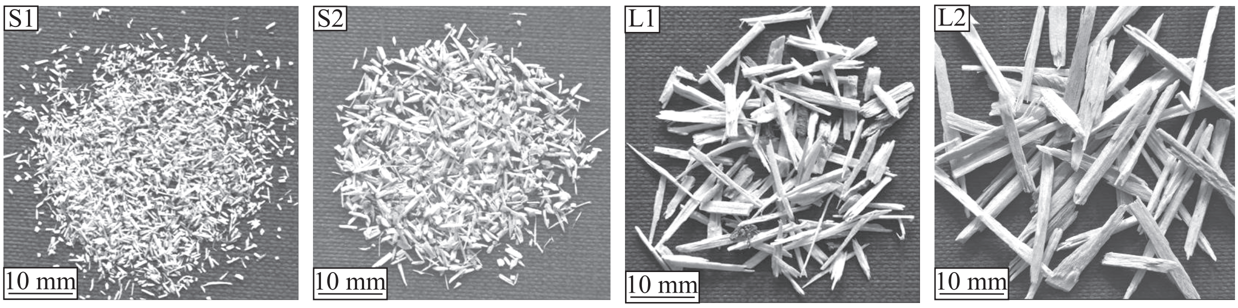

Fig. 1. Screened wood particles of S1, S2, L1 and L2 sizes (see text)

Sample preparation

All the particles were dried at 80 °C in an air-circulation oven BINDER ED240 for 24 h before mixing process in order to achieve a moisture content of less than 3 %. Next the particles were mixed with PE-LD at 40 % by weight. Test specimens were made by injection molding using a screw injection molding machine Wh-80 Ap. The temperature profile was 155, 180 and 175 °C. The injection pressure time, hold pressure time and cooling time were 5, 4 and 50 s, respectively. To minimize mechanical degradation of particles during molding, the diameter of the injection die was enlarged to 4.5 mm, and the diameter of the sprue bush to 8 mm. The cross section of the runner and the gate was 10×10 mm^2 and 6×6 mm^2, respectively.

For determining the effect of cross-section size of injection molded pieces, three cross-section areas were assumed: (1) 40 mm^2 (4×10 mm^2); (2) 90 mm^2 (6×15 mm^2); and (3) 160 mm^2 (8×20 mm^2). The specimens with these three cross-section sizes were made. Dimensions of those of 40 mm^2 cross-section were according to EN ISO 527, and dimensions of those of 90 mm^2 and 160 mm^2 cross-sections were adequately larger. After processing the specimens were stored in controlled conditions (50 % relative humidity and temperature 20 °C) for two weeks prior to testing.

Methods of testing

The mechanical properties of the tested WPC were evaluated in relation to tensile, flexural and impact properties. Tensile and flexural tests were performed according to EN ISO 527 and EN ISO 178, respectively, using an Instron 3367 machine. The constant, averaged cross-head speed of 2 mm/min for different sizes of specimen was used, which allowed to obtain a speed of elongation about 1 % of measurement base per minute. Unnotched Charpy impact strength tests were conducted according to EN ISO 179 with PSd 50/15 impact test device. Ten replicates were run for each test. All tests were performed at room temperature (20 °C) and at constant relative humidity (50 %).

RESULTS AND DISCUSSION

Mean values of the tensile modulus and strength, the flexural modulus and strength, and the impact strength of tested WPC are given in Figure 2. Error bars represent one standard deviation based on ten specimens.

Two-way analysis of variance (ANOVA) was conducted to determine the significance of the effects of particle size and cross-section size on the WPC mechanical properties (Table 3). Results of this analysis show that all mechanical properties vary significantly with particle size and specimen cross-section size. The interaction between these two variables is significant only for the tensile and flexural moduli.

T a b l e 3. Two-way ANOVA test on the effects of WP size and specimen 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*)	<0.0001*)
Cross-section size	0.0258*)	<0.0001*)	<0.0001*)	<0.0001*)	<0.0001*)
WP size x cross-section size	0.0056*)	0.3672ns	0.0025*)	0.3456ns	0.9692ns

*) Denotes significance at 0.01; ns — non significant at 0.05.

Tukey's test was applied to evaluate the statistical significance between mean values of mechanical properties of WPC with different particle sizes, determined on specimens with different cross-section sizes. Values with the same letter for given property (Fig. 2) are not significantly different at the 5 % significance level.

Effect of particle size

Generally, increasing particle size improves the WPC mechanical properties. Tensile and flexural properties increase gradually with increasing particle size (sieve analysis) from S1 to L1 and decrease when particle size increases to L2, but values of these properties for the WPC with L2 particles are greater than those for the WPC with S2 particles. The tensile and flexural moduli of WPC with larger (L1 and L2) particles are 27 % and 25 % greater, on average, than those of WPC with smaller (S1 and S2) particles. The relative difference between the modulus of WPC with larger and smaller particles is more pronounced when the specimen cross-section is larger. The tensile and flexural strengths of WPC with larger particles are 14 % and 15 % greater, on average, than those of WPC with smaller particles. In this case, the relative difference between the strength of WPC with larger and smaller particles does not depend on specimen cross-section size.

The improvement of the mechanical properties of tested WPC with increasing WP size is a result of particle geometry. According to mechanics of fiber-reinforced composite materials, one of important factors affecting their mechanical properties is a fiber aspect ratio defined as a fiber length-to-thickness ratio. Fibers with a higher aspect ratio enhance stress transfer from the polymer matrix to the fibers and ultimately improve the composite mechanical properties. Values of this ratio for WP used in the study were 20.2 and 21.4 for L1 and L2 particles, respectively, and 14.9 and 16.3 for S1 and S2 particles, respectively (Table 2). Improving the WPC mechanical properties by particles with a higher aspect ratio was also observed for wood-PP [1, 3] and wood/PE-HD [7] composites.

The tensile and flexural properties of tested WPC with L2 particles are worse than those of WPC with L1 particles. The relative decreases amount to 11 % and 7 % on

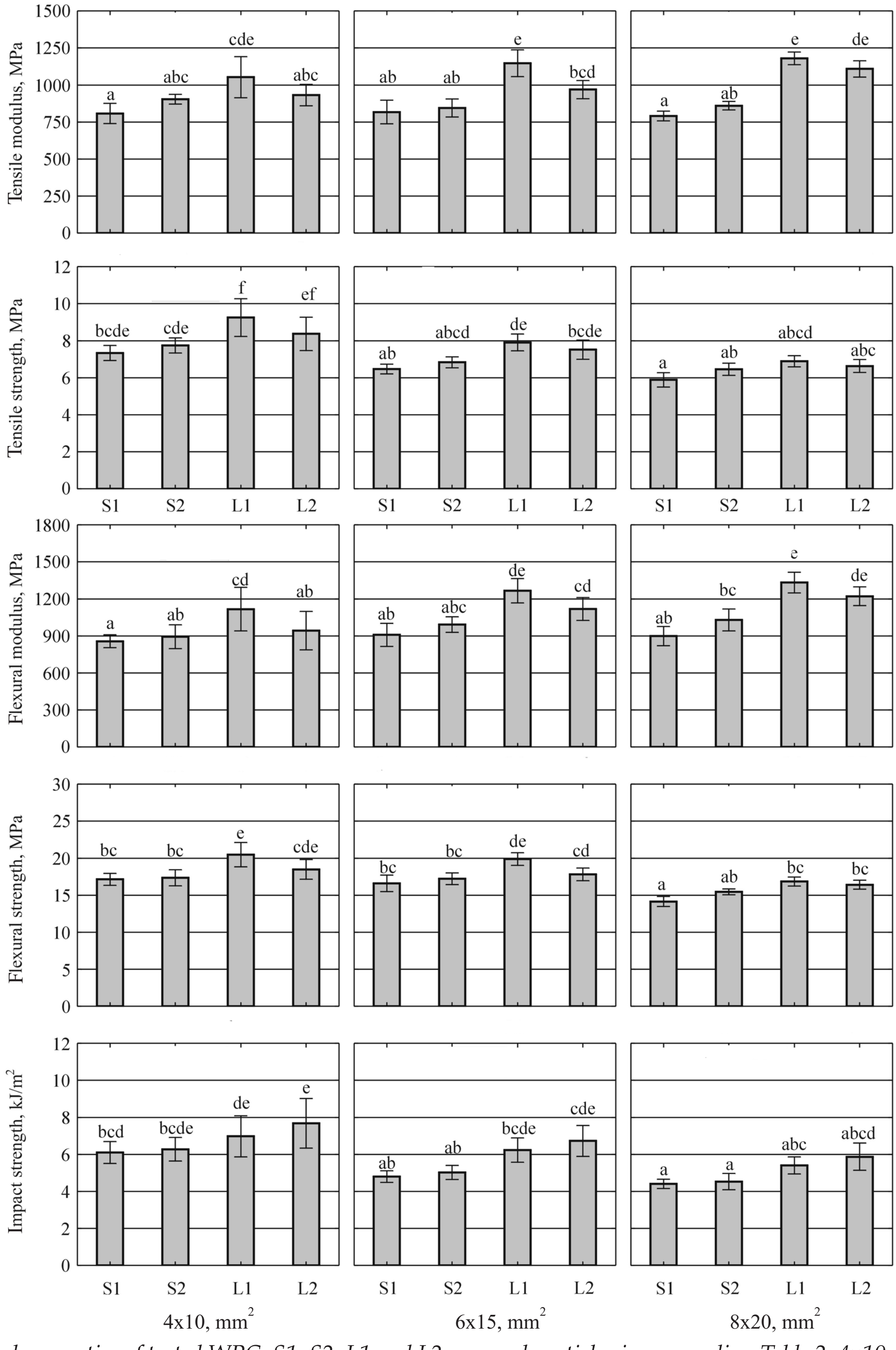

Fig. 2. Mechanical properties of tested WPC; S1, S2, L1 and L2 — wood particle sizes according Table 2; 4×10 = 40 mm², 6×15 = 90 mm² and 8×20 = 160 mm² — specimen cross-section sizes. Mean values with the same letter for given property are not statistically different at the 5 % significance level

average for the elastic moduli and strengths, respectively. These decreases are probably due to the fact that too large particles were breaking during the mixing process.

The WPC impact strength increases gradually with increasing particle size from S1 to L2, and for the WPC with larger particles it is, on average, by 25 % higher than for the WPC with smaller particles.

Effect of specimen cross-section size

The effect of specimen cross-section size on the WPC mechanical properties is presented in Figure 3. The variation of the WPC tensile modulus is different for WPC with larger and smaller particles. For the WPC with larger particles (curves 3 and 4) this modulus increases

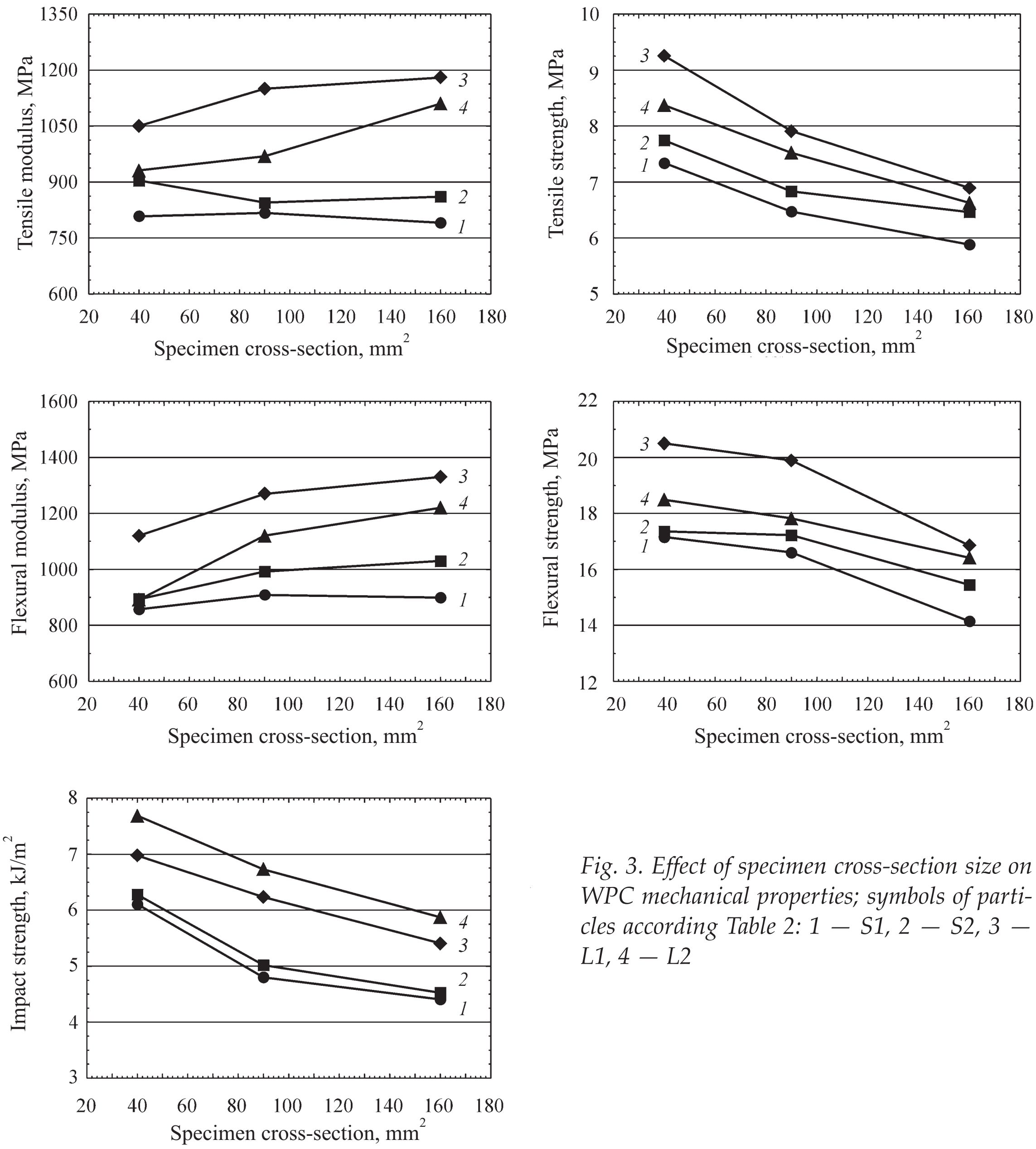

Fig. 3. Effect of specimen cross-section size on WPC mechanical properties; symbols of particles according Table 2: 1 — S1, 2 — S2, 3 — L1, 4 — L2

gradually with increasing cross-section size. The modulus determined for specimens of 160 mm^2 cross-section is on average 15 % greater than that determined for specimens of 40 mm^2 cross-section. For WPC with smaller particles there is a different tendency (curves 1 and 2): the tensile modulus decreases, on average 3 %, when cross-section size increases from 40 to 160 mm^2. The WPC flexural modulus increases gradually with increasing cross-section size. Its value determined for specimens of 160 mm^2 is on average 28 % and 10 % greater than the value determined for specimens of 40 mm^2, for the WPC with larger and smaller particles, respectively.

The increase in specimen cross-section size results in the decrease in the WPC tensile, flexural and impact strengths. These strengths determined on specimens of 160 mm^2 cross-section are on average by 20 %, 15 % and 25 % smaller than those determined for specimens of 40 mm^2 cross-section. The decrease in these strengths is almost the same for the WPC with larger and smaller wood particles.

A scatter of results for the determined WPC mechanical properties is affected by both particle size and specimen cross-section size. Standard deviations are generally higher when particle size is larger (Fig. 2). Their increase with increasing particle size is the highest for the results determined on the specimens with the smallest cross-section.

Standard deviations are lower for the results determined on specimens with larger cross-sections. The decrease in standard deviations with increasing cross-section size is greater for WPC with larger particles size. So, to sum up, the smaller the particle size and the larger the specimen cross-section size, the lower the standard deviation. Taking it into consideration, it is preferable to use specimens with a cross-section larger than a standard cross-section of 4×10 mm^2

($40\ mm^2$) to determine the mechanical properties of the WPC with larger wood particles — namely, no less than $6\times15\ mm^2$ ($90\ mm^2$) for WPC with L1 particles, and $8\times20\ mm^2$ ($160\ mm^2$) for WPC with L2 particles. This is especially so when determining the WPC strength for which the results achieved for specimens with a larger cross-section have lower values.

CONCLUSIONS

Industrial wood particles used for manufacturing three-layer particleboards can be a good raw material to make composites with PE-LD by an injection molding method. These WPC have good mechanical properties, which depend on wood particle size and a cross-section area of injection molded pieces. The large-sized particles, used for manufacturing a core particleboard layer, allow to make WPC with better properties than the small-sized particles used for manufacturing face particleboard layers. It is a result of a greater aspect ratio of larger wood particles. The tensile and flexural elastic moduli determined on specimens with a larger cross-section area are in general greater while tensile, flexural and impact strengths are lower than those determined for specimens with a smaller cross-section area.

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