Research Article

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The effects of fiber length and fiber loading on the mechanical properties of wood-plastic (polypropylene) composites

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Abstract: This study examined the effects of wood pulp fiber length (short, medium, and long), and fiber loading (27%, 37%, 47%, and 0% [non-reinforced PP]) with 3% maleic anhydride-grafted polypropylene on the mechanical properties of wood-plastic composites (WPCs). Polypropylene and fibers were compounded into pellets using a counter-rotating twin-screw extruder and test specimens were prepared by injection molding. The results show that increases in fiber length and fiber loading significantly increased ($P < 0.05$) the mechanical properties of the WPCs (MOE and tensile modulus). The behavior of the composites against MOR and impact strength varied according to fiber length and loading level. In general, the tensile strength was observed to be the same.

Key words: Fiber loading, fiber length, mechanical properties, wood-plastic composite

Introduction

Wood-plastic composites (WPCs) are composed of a mixture of plastic, such as polypropylene, and low-value wood (sawdust) and other cellulose-based fiber fillers or reinforcers, such as pulp fibers. Coupling agents, such as maleic anhydride-grafted polypropylene (MAPP), are added in small amounts to facilitate adhesion between the natural fibers and plastic components. WPCs are used in a variety of applications, including the automotive and construction industries. In construction, they are primarily used in both structural and non-structural applications, such as decking, fencing, and railing.

Among the many fillers or reinforcers available, natural fillers or reinforcers have several advantages, such as a renewable nature, low cost, low density, high specific strength and stiffness, CO_2 sequestration, low energy consumption, and low wear on machinery (Mohanty et al. 2002; Samir et al. 2005). Natural fibers can be divided into different classes depending on their origin, including wood, vegetable, animal, etc. Among these, wood fibers are more commonly used because they are easier to obtain, as compared to others.

Despite the many advantages that wood fibers offer, their hydrophilicity is a major hindrance for

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widespread use in WPCs. They not only increase the moisture intake of WPCs, but also affect the interfacial adhesion of wood fibers with the polymer matrix. Hence, in order to widen the applicability of WPCs and to produce high-performance WPC, the interfacial strength must be improved (Bakraji and Salman 2003; Wechsler and Hiziroglu 2007).

Much research has been conducted on the natural reinforcing filler characteristics used in thermoplastic materials, so as to produce high-performance composites. Many researchers reported that fiber loading and fiber structure, such as length and ratio of fiber length to width (aspect ratio), also affect the overall properties of biocomposites (Stark and Rowlands 2003; Klyosov 2007; Migneault et al. 2008; Mengeloğlu and Karakuş 2008; Bouafif et al. 2009). Other researchers have indicated that increasing the aspect ratio provides higher tensile and flexural strength, and a greater modulus for WPCs (Stark and Rowlands 2003). The present study investigated the effects of fiber length and fiber loading on the mechanical properties of WPCs.

Materials and methods

Materials

Softwood Kraft pulp fibers (70% pine and 30% spruce) were obtained from a tissue producer (Now-Zohor) in Iran. The pulp was bleached via the ECF process (without using Cl). It has an average fiber length of 2.35 mm, pH of 6, and consists of 0.25% ash.

Homopolymer polypropylene (PP) was obtained from Arak Petrochemical Company (Iran). The melt flow rate of PP (trade name P10800) was 7-10 g 10 min^{-1} at 190 °C.

MAPP (Aldrich 427845) was used as a coupling agent.

Fiber Separation

Very small pieces of pulp sheets were placed in warm water for 48 h to soften, and then were passed through mesh. Fiber length, as measured by light microscopy, varied between 1.5 and 3 mm. Thus, the fibers were characterized as follows: short (≤1 mm), medium (1-2 mm), and long (≥2 mm) (Table 1). Distribution was performed using mesh sizes of 14 and

Table 1. The experimental design and detail statistical information about fiber characteristics.

Treatments (composites)[a]		Detailed statistical information about fiber characteristics				
Fiber loading (%)	Fiber length (mm)	Average fiber length (mm)	Standard deviation	Average fiber width (mm)	Standard deviation	Aspect ratio (length/width)
27 37 47	Short (<1)	0.73	0.21	0.031	0.0052	23.54
0 (control)						
27 37 47	Medium (1-2)	1.46	0.50	0.027	0.0054	54.07
0 (control)						
27 37 47	Long (>2)	2.30	0.50	0.028	0.0058	82.14
0 (control)						

[a]: Maleic anhydride grafted polypropylene for all reinforced samples was permanent (3%).

20. Fibers that passed through mesh size 14, but not mesh size 20, were designated as long (≥2 mm) and fibers that passed through mesh size 20 were designated as medium (1-2 mm). Due to the lack of short fibers, some long and medium fibers were chopped using a laboratory electrical rotary mill to obtain short fibers (<1 mm). The ratio of fiber length to width (aspect ratio) of the fibers was determined. All the fibers were dried on aluminum foil in a temperature-controlled room for 48 h, and then were defibrillated in a large sealed plastic flask using an air pump. Further drying of the defibrillated fibers was performed in a kiln to reduce the moisture level to <6%.

Composite preparation

The components of each sample (PP, MAPP, and fibers) were pre-mixed to prepare homogeneous compounds and were blended in a counter-rotating twin-screw extruder (Dr. Collin System) at a screw speed of 50 rpm at 180 °C. The mix was removed from the mixing bowl, cooled in water, and granulated into pellets. The pellets were dried at 105 °C for 24 h before injection molding. Finally, the pellets were injection molded (Imen Machine Co., Iran) at 175 °C and a pressure of 10 MPa.

Statistical analysis

Statistical analysis was performed using ANOVA (SPSS). Fiber loading levels were 27%, 37%, and 47% (wt%), with 3 different fiber lengths (short, medium, and long); MAPP for all reinforced samples was 3%. In all, 9 formulations with control samples (non-reinforced or pure PP) were determined by ANOVA, using the variables of fiber length (short, medium, and long) and loading (27%, 37%, and 47%). The formulation design is given in Table 1. Testing of each property was performed using 4 replicates of each formulation, except for the impact property, which had 5 replicates. Property means were compared using Duncan's new multiple range test at the 95% confidence level, as shown in Figures 1-5.

Mechanical testing

All the materials were kept at 23 °C and 50% humidity before mechanical testing. The flexural tests were performed on an Instron 1186 universal testing machine, according to ASTM test method D-790. The crosshead speed was set at 5 mm min^{-1}. Sample dimensions for flexural tests were 105 ´ 10 ´ 10 mm. The tensile properties of each specimen were tested with an INSTRON 1186 universal testing machine, according to ASTM test method D-638. The crosshead speed was set at 5 mm min^{-1}. The sample dimensions for tensile property testing were 145 ´ 10 ´ 4 mm. The notched Izod impact strength test was conducted with a SANTAM machine, according to ASTM test method D-256. The sample dimensions for the notched Izod impact test were 60 ´ 12 ´ 6 mm.

Results

Relationship between fiber length and fiber loading, and mechanical properties

MOR

As shown in Figure 1, the effect of fiber length and loading level on the MOR of PP-Kraft pulp composites varied. Among the specimens, the 27% medium fiber-, 37% long fiber-, and 47% medium fiber-reinforced composites had the highest MOR; however, these values were not significantly higher than for non-reinforced PP.

MOE

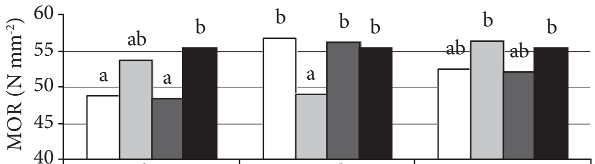
Figure 2 shows the relationship between MOE, and fiber length and fiber loading. MOE increased as fiber loading increased for the same fiber length. Additionally, except for 37% medium fiber-reinforced composite, MOE increased as fiber length increased for the same fiber loading. The highest MOE was observed for 47% long fiber-reinforced composite. Moreover, the MOE of all the reinforced specimens was higher than for pure PP.

Tensile modulus

Similar to MOE, the tensile modulus also increased as fiber loading increased for the same fiber length (Figure 3). Furthermore, the tensile modulus increased as fiber length increased for the same fiber loading. The tensile modulus of all the composite specimens was higher than for pure PP and the highest modulus was observed for 47% long fiber-reinforced composite.

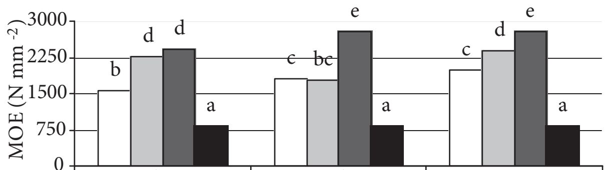
Tensile strength

As shown in Figure 4, the tensile strength of almost all the samples, including pure PP, was the same, except for 27% small fiber-reinforced



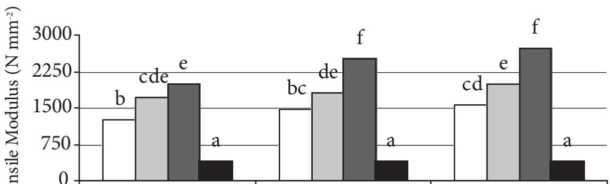
	Short	Meduim	Long
□ 27%	48.8	56.8	52.4
▪ 37%	53.6	48.9	56.3
▪ 47%	48.3	56.2	52.1
■ Control	55.3	55.3	55.3

Figure 1. The effect of fiber length and fiber loading on MOR properties. Duncan's multiple range tests is depicted at the top of the columns. The different alphabetical designations indicate that there is a significant difference between different treatments (composites), whereas the common alphabetical designation indicates no significant difference (P < 0.05).



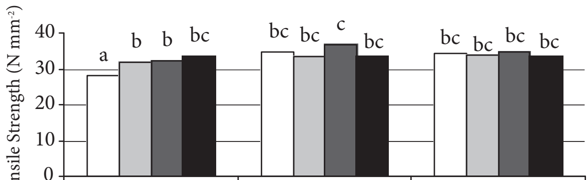
	Short	Meduim	Long
□ 27%	1576.3	1815.2	1999.8
▪ 37%	2257.9	1789.7	2382.2
▪ 47%	2418.8	2774.3	2793.8
■ Control	831	831	831

Figure 2. The effect of fiber length and fiber loading on MOE properties. Duncan's multiple range test is depicted at the top of the columns. The different alphabetical designations indicate that there is a significant difference between treatments (composites), whereas the common alphabetical designation indicates no significant difference (P < 0.05).



	Short	Meduim	Long
□ 27%	1243.8	1480.1	1563.4
▪ 37%	1729.1	1809.7	1974.5
▪ 47%	1996.3	2514.9	2722.8
■ Control	412.9	412.9	412.9

Figure 3. The effect of fiber length and fiber loading on tensile modulus properties. Duncan's multiple range test is depicted at the top of the columns. The different alphabetical designations indicate that there is a significant difference between different levels of treatments (composites), whereas the common alphabetical designation indicates no significant difference (P < 0.05).



	Short	Meduim	Long
□ 27%	28.1	34.7	34.4
▪ 37%	31.8	33.5	34
▪ 47%	32.4	36.8	34.8
■ Control	33.27	33.27	33.27

Figure 4. The effect of fiber length and fiber loading on tensile strength properties. Duncan's multiple range test is depicted at the top of the columns. The different alphabetical designations indicate that there is a significant difference between different treatments (composites). Composites with a common alphabetical designation are not significantly different (P < 0.05).

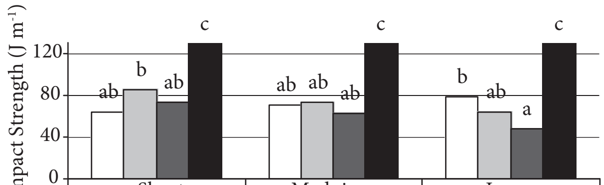
composite. This was also inferred by Duncan's multiple range test results (top of Figure 4), which show that there was a significant difference between short fibers + fiber loading of 27% and all other formulations.

Impact

As shown in Figure 5, the impact property values of all the reinforced composite specimens were lower than for non-reinforced PP. In general, higher fiber loading was associated with lower impact property values, except for 27% short fiber-reinforced composite. For long fiber composites, impact strength decreased as fiber loading increased, whereas for short and medium fiber composites the effect of fiber length and loading on impact strength was variable.

Discussion

The results of the present study on polypropylene-Kraft wood pulp composites with variations in fiber length and fiber loading show that the 2 parameters played an important role in the mechanical properties, especially MOE and tensile modulus (Figures 2 and 3).



	Short	Meduim	Long
□ 27%	63.6	70.8	77.83
▫ 37%	84.3	72.3	63.16
■ 47%	73.6	62.6	48.1
■ Control	128.3	128.3	128.3

Figure 5. The effect of fiber length and fiber loading on impact strength properties. Duncan's multiple range test is depicted at the top of the columns. The different alphabetical designations indicate that there is a significant difference between different levels of treatments (composites). Groups with a common alphabetical designation are not significantly different ($P < 0.05$).

The effect of fiber length and fiber loading level on MOR and impact strength varied (Figures 1 and 5). This variability might have been due to a number of factors, such as molecular mass, cross-linking and ramification, crystallinity and crystalline morphology, co-polymerization, plastification, molecular orientation, and reinforcement (Caraschi and Leão 2002; Klyosov 2007). Hence, further research is required to study the variable effect of fiber length and fiber loading on MOR and impact strength. In general, the impact strength of the composites was lower than that of pure PP (Figure 5). This is likely due to the fact that the wood particles acted as stress concentrators and decreased the impact strength; this is consistent with published data (Kokta et al. 1989; Stark and Rowlands 2003).

The effect of fiber loading and fiber length on MOE and tensile modulus, as stated above, was positive. In general, at the same fiber length, the tensile modulus and MOE increased as fiber loading increased, and at the same fiber loading MOE and tensile modulus also increased (Figures 2 and 3). This is true for WPCs in which fillers added to a polymer restrains the movement of its chains, thereby increasing its modulus (Pilla et al. 2007).

Generally the tensile strength of filled composites is lower than for pure polymer (Zuiderduin et al. 2003); however, in the present study, the tensile strength of all the composites, except 27% short fiber-reinforced composite, was the same (Figure 4). This is due to the use of the coupling agent MAPP, which provided good interfacial adhesion. Thus, it can be inferred that both fiber length and fiber loading did not have any significant effect on the tensile strength of the composites.

Finally, we can conclude that the effect of fiber length and fiber loading on MOR and impact strength was variable, but they had a positive effect on tensile modulus and MOE. Overall, tensile strength was observed to be the same in all the composite specimens due to good interfacial adhesion.

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