Bamboo Fiber-Reinforced Polypropylene Composites: A Study of the Mechanical Properties

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ABSTRACT: A new type of bamboo fiber-reinforced polypropylene (PP) composite was prepared and its mechanical properties were tested. To enhance the adhesion between the bamboo fiber and the polypropylene matrix, maleic anhydride-grafted polypropylene (MAPP) was prepared and used as a compatibilizer for the composite. The maleic anhydride content of the MAPP was 0.5 wt %. It was found that with 24 wt % of such MAPP being used in the composite formulation, the mechanical properties of the composite such as the tensile modulus, the tensile strength, and the impact strength all increased significantly. The new composite has a tensile strength of 32–36 MPa and a tensile modulus of 5–6 GPa. Compared to the commercially available wood pulp board, the new material is lighter, water-resistant, cheaper, and more importantly has a tensile strength that is more than three times higher than that of the commercial product. © 1998 John Wiley & Sons, Inc. J Appl Polym Sci 69: 1891–1899, 1998

Key words: bamboo; composites; mechanical properties

INTRODUCTION

As the world economy ascends to a new stage, demand for wood will increase proportionally. Current statistics show that the timber trade in the world market has exceeded 1500 million m^3.[1] The demand for good-quality timber will lead to a nonrenewable logging of tropical hardwood forests in many developing countries, and give rise to serious global concern, especially in Asian countries. Indonesia's current dominance of the export market is expected to end within 20 years at present rates of logging, while Thailand has banned all commercial logging in its hardwood forests.[2,3] Therefore, a sharp rise in the cost of natural timber products is expected in the near future. With timber substitutes available in the form of wood chipboard, the demand for wood has been alleviated to some extend, but the raw material is still mainly wood, and the mechanical properties are not very satisfactory.[4,5]

The objective of this study is to develop a new type of composite material—bamboo fiber-reinforced plastic (BFRP) composite—as a cheap substitute for wood. Bamboo fiber was chosen as the reinforcement because bamboo is an abundant natural resource in Asia, and its overall mechanical properties are comparable to those of wood.[6] Furthermore, bamboo grows to its mature size in only 6–8 months, whereas wood takes about 10 years. Polypropylene was chosen as the matrix of the composite because it is a relatively cheap thermoplastic with reasonable mechanical properties.

The interfacial morphology between bamboo fiber and the PP was reported in our earlier study.[7] In this article we will report the mechani-

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cal properties of the composites, such as the tensile strength, the tensile modulus, the yield strength at the break, and the impact strength. To enhance the bonding between the bamboo surface and the PP matrix, maleic anhydride was grafted onto PP, and the detailed procedure was also discussed in this article.

EXPERIMENTAL

Materials

Commercial polypropylene (PP) and the maleated polypropylene (MAPP) were used as the matrix of the composite. The PP powder, Profax 6201, which was obtained from Himont Chemical, Hong Kong Ltd., has a density of 0.920 g/cm^3 and a melt flow index of 20. The maleic anhydride-modified polypropylene powder, MAPP, was prepared in the laboratory. Maleic anhydride (MAH) was purchased from Aldrich, Madison, WI, and was used as received without purification. Benzoyl peroxide (BPO), used as an initiator, was purchased from Acros, USA, and it was purified by reprecipitation with methanol from chloroform solution. AR grade toluene and acetone were obtained from Fisher, USA, and were used as received without further purification. The stabilizer added to the polymer prior to processing was Irganox 1010, a tertiary butyl hydroxyhydrocinnamate, from Ciba-Geigy Corporation Ltd., Hong Kong.

The bamboo used in this work belongs to the species of Bambusa Paravariabilis, which grows abundantly in Asia. Bamboo chips were produced by means of a wood planer, which were then ground into smaller pieces with a Toshiba MX-301 blender followed by an IKA-Analytical mill. The finer bamboo chips were first dried in a vacuum oven at the temperature of 80°C and under the pressure of 180 mmHg for 48 h. They were then separated with a set of Endecotts test sieves with the aperture sizes ranging from 500 microns to 2 mm. Five sizes of bamboo fiber were employed in the BFRP composites: (1) less than 500 μm (2) 500–850 μm, (3) 850 μm to 1 mm, (4) 1–2 mm, and (5) a mixture of bamboo chips less than 2 mm.

Grafting Procedures

MAPP employed in this work was prepared by solution surface grafting.[8,9] The reaction was carried out in a three-neck-round-bottom flask equipped with a condenser, a thermometer, and dry nitrogen gas inlet. A Cimarec Thermolyne hot plate was employed for heating and stirring. The reaction temperature was maintained at 80°C with the accuracy of ±0.5°C by using a contact thermometer in a water bath. Eighty grams of polypropylene powder was dispersed in toluene (600 mL) in the reactor. Nitrogen gas was purged throughout the reaction to remove dissolved oxygen. Eight grams of maleic anhydride, predissolved in hot toluene at 50°C, was added to the reactor. After 2 min of homogenization in the reaction media, 0.8 g benzoyl peroxide, predissolved in hot toluene at 50°C, was added to the reactor. The reaction was continued for 8 h under vigorous stirring with a magnetic stirrer. At the end of the reaction, the solvent was separated with a filter, and the product was washed five times with acetone to eliminate the unreacted maleic anhydride. The grafted polypropylene product was dried in a vacuum oven at the temperature of 60°C and under the pressure of 180 mmHg for 3 h.

The amount of maleic anhydride grafted onto polypropylene was calculated according to the method reported by Gaylord.[9,10]

Preparation of BFRP Composites

All raw materials were dried in an oven at 80°C and 180 mmHg vacuum for 2 h to expel moisture before they were used for compression. A 0.5 wt % stabilizer was added to the polymer prior to mixing.

The apparatus used to disperse the fibers within the polymer matrix was a Haake Mixer 3000, equipped with a roller mixer-measure head with precisely controlled temperature and rotation speed.

The mixing conditions, such as the ratio of the raw materials, temperature, speeds, and compression time were scrutinized. The torque, temperature, energy, and other mixing parameters, which are related to the viscoelastic properties of the materials and the efficiency of mixing process, were monitored. After mixing, the materials were removed to a compression mold.

Molding Procedures

A 200 × 200 mm stainless steel mold was machined. The mold was assembled, cleaned, and covered with Glad bake paper. The mixture of bamboo chips, PP, and MAPP was homogeneously distributed into the mold, then were compression molded with a hot press (PHI).

After a series of experiments, the optimized molding conditions were as follows: temperature, 210°C; compression pressure during heating and cooling, 5 MPa; preheating time, 5 min; heating time, 20 min. After compression molding, the molded boards were kept under ambient condition for further tests.

Tensile Test

Tensile tests were performed with a Universal Testing Machine (UTM), Sintech 10/D tensile tester, USA, and followed by ASTM (American Society for Testing and Materials) standard D639–90. Tensile specimens of bamboo, PP, MAPP, and the composites were machined in dumb-bell shape, following the suggested dimensions of ASTM D639–90 specimen Type I. Five specimens for each sample were tested. The width and thickness of the narrow section for each specimen were measured with an electronic digital caliper. The standard testing conditions were: tensile speed: 3.00 mm/min.; load limit HI: 50 KN; extensometer: 25.00 mm 50% extension.

The stress–strain curve of the specimen was recorded by the attached computer. The tensile strength, the elongation at break, and the tensile modulus were calculated from the stress–strain curve.

Charpy Impact Test

A Charpy impact test was performed with a CEAST pendulum impact tester, England. The testing method was consistent to ISO method 179–1982(E). Notched specimens of the composites were in agreement with the dimensions of ISO 179–1982 type 2A. The notch was cut in the middle of the specimen with a CEAST notching machine. A 0.5 J pendulum was used to break the specimens. The impact energy was recorded. After testing, the crack width of each broken specimen was measured with an electronic digital caliper. The Charpy impact strength was obtained from dividing the impact energy by the cross-sectional area. The unit of the impact strength is KJ/m^2. To obtain a reasonable value, 15 specimens for each sample were tested, and the average impact strength for each sample was calculated.

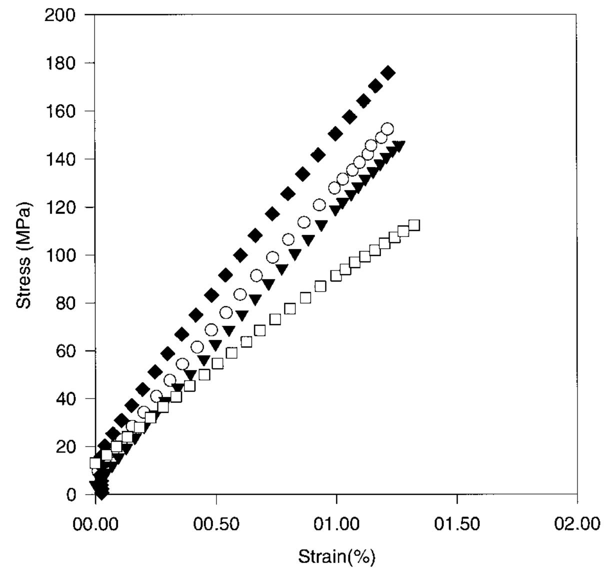


Figure 1 The stress–strain curves of bamboo specimens: ○ specimen 1; □ specimen 2; ▼ specimen 3; ◆ specimen 4.

Scanning Electron Microscopy (SEM)

A JOEL 6300 scanning electron microscope with resolution of 70 nm was used to study the interfacial morphology of BFRP composites. The interfacial adhesion between fiber–matrix was investigated by examining the tensile fracture surface of different types of BFRP composites. All samples were dried at the temperature of 80°C in a vacuum oven for 12 h, then sputter coated with a layer of approximately 100 Å gold. The micrographs were captured with the Polaroid type films.

RESULTS AND DISCUSSION

Mechanical Properties of Raw Materials

The stress–strain curves of four different kinds of bamboo, PP, and MAPP are shown in Figures 1 and 2. Tensile strength, elongation at break, and tensile modulus; calculated from the stress–strain curves are shown in Figures 3–7 and in Figures 11–13.

Effect of Bamboo Fraction

The influence of fiber fraction on the tensile modulus and the tensile strength are illustrated in Figures 3 and 4, and the influence on the impact strength is shown in Figure 5.

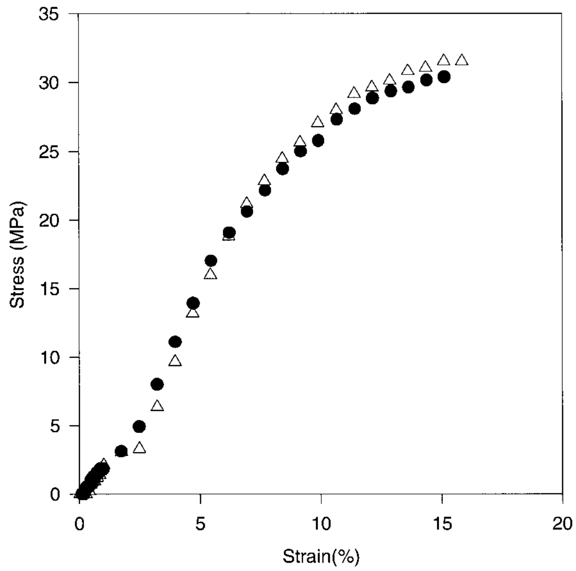


Figure 2 The stress–strain curves of two types of PP: ● nonmodified; △ MAPP.

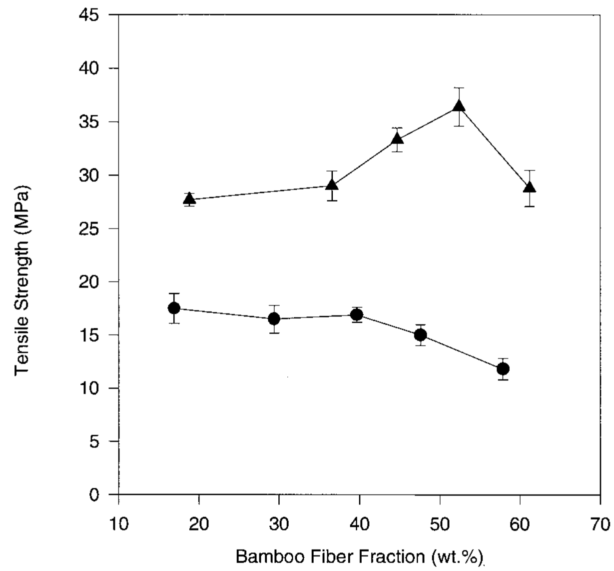


Figure 4 Effect of bamboo fiber fraction on the tensile strength of BFRP composites: ● BF/PP composites; ▲ BF/MAPP composites.

It can be seen, in Figure 3, that the tensile modulus of the bamboo/MAPP/PP composites increases with bamboo content up to 65 wt %; whereas, the modulus of the bamboo/PP composites does not vary significantly with changing bamboo fraction. A tensile modulus of 3.4 GPa is noted at about 50 wt % bamboo fiber in the PP composite; however, at the same composition, the values with MAPP is higher.

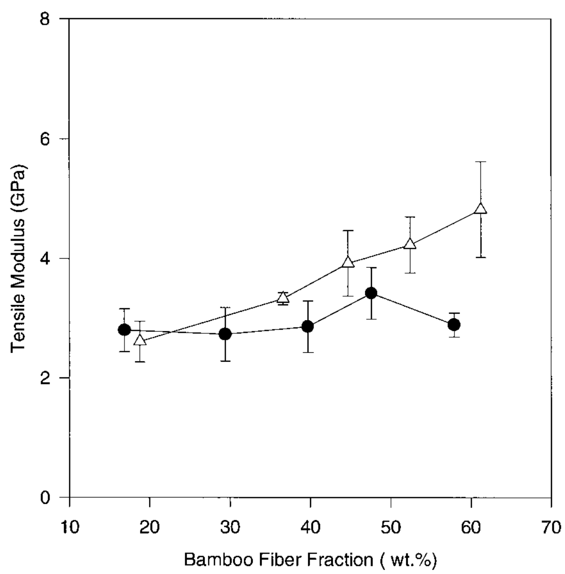


Figure 3 Effect of bamboo fiber fraction on the tensile modulus of BFRP composites: ● BF/PP composites; △ BF/MAPP composites.

Figure 4 shows that the tensile strength of MAPP/PP composites yields to a maximum value of 36 MPa at about 50 wt % bamboo fiber. On the other hand, for PP composites, the tensile strength decreases slightly.

The above results can be explained by the modified Law of Mixtures equation, which is commonly applied in studying tensile properties of the composites with discontinuous, short fiber:

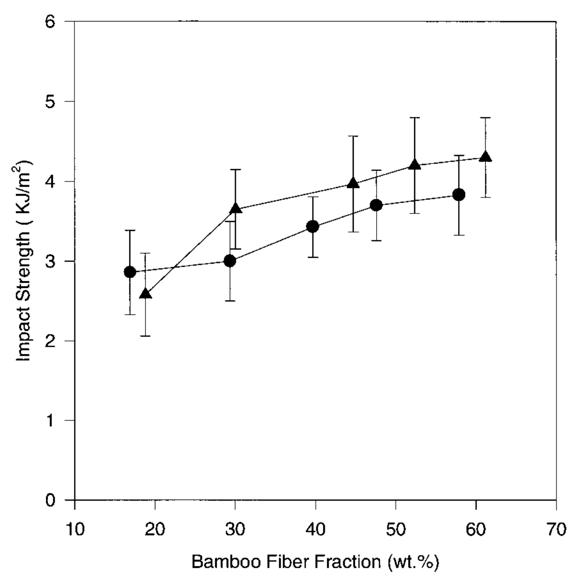


Figure 5 Effect of bamboo fiber fraction on the impact strength of BFRP composites.

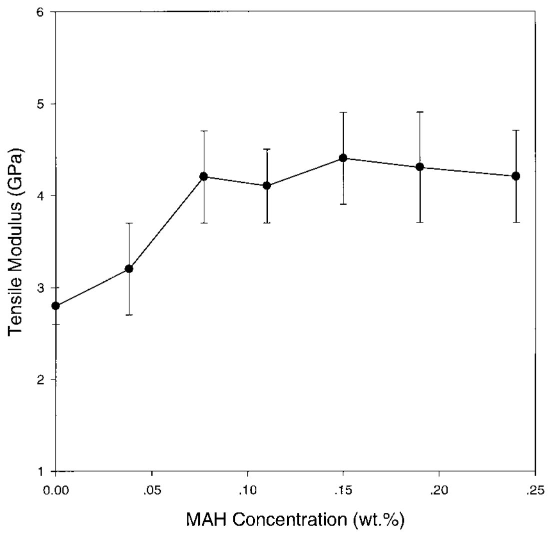


Figure 6 Effect of MAH content on the tensile modulus of BFRP composites (50 wt % BF).

$$\sigma_c = KV_f\sigma_f\left(1 - \frac{L_c}{2L}\right) + (1 - V_f)\sigma_m^*$$

$$L_c = \frac{D\sigma_f}{2\tau} \qquad (2)$$

where σ_c is the tensile strength of the composite, K is an empirical fiber efficiency parameter, v_f is the volume fraction of fiber, σ_f is the tensile strength of the fiber, σ_m^* is the tensile strength of the matrix at breaking strain of the fiber, L is the fiber length, L_c is the critical fiber length, D is the diameter of the fiber, and τ is the interface shear strength.[11–13]

From eqs. (1) and (2), it is apparent that the value of σ_c increases with increasing τ, when K, L, and D are assumed constant in all systems. This implies that the improvement of adhesion between the bamboo fiber and the polymer matrix increases the tensile strength of the composites.

Effect of MAPP Content

One of the main factors that affects the mechanical properties of the bamboo fiber-reinforced composites is the adhesion between the fiber and the matrix. It is known that the use of the compatibilizer can improve the adhesion, and hence, improve the mechanical properties of the composites. Because bamboo surface is hydrophilic characterized by polar hydroxyl groups and also because PP is hydrophobic polyolefins, the adhesion between the two materials is expected to be rather poor. Therefore, in this study, we used the MAPP as the compatibilizer to improve the adhesion because the maleic anhydride strongly associates with the hydroxyl groups on the bamboo surface.

To study the effect of MAPP content on the mechanical properties, the bamboo fraction was kept at 50 wt %, and the ratio of PP to MAPP was changed. The results of the effect of MAPP on the mechanical properties are shown in Figures 6 and 7. Because the maleic anhydride (MAH) content of the MAPP is 0.5 wt %, we have therefore converted the MAPP content into MAH content in the composites, and, consequently, Figures 6 and 7 are the plots of mechanical properties as a function of the MAH content in the composites.

Referring to Figure 6, it is found that the tensile modulus increases slightly with increasing MAH content.

However, referring to Figure 7, one should find a remarkable increase in the tensile strength with the MAH content up to 0.12 wt %, which is equivalent to 24 wt % of MAPP in the composite. A continuous improvement in the strength was observed as the MAH content was up to 0.25 wt %.

Referring to the results in Figures 6 and 7, it is believed that the MAPP acts as a compatibilizer in the system, which improves the interfacial adhesion in BFRP composites and provides better bonding (e.g., hydrogen bonding) between MAPP

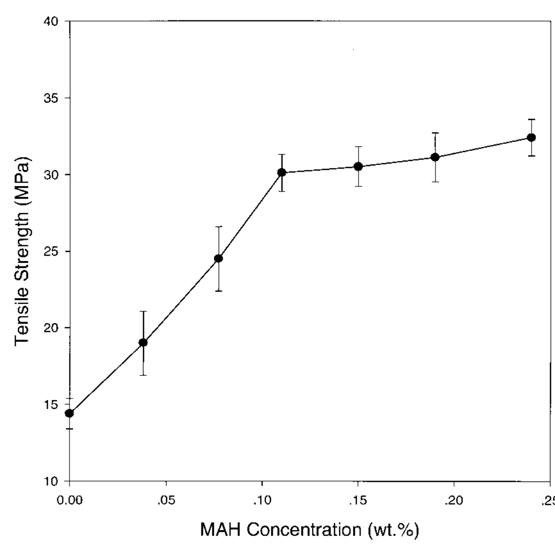


Figure 7 Effect of MAH content on the tensile strength of BFRP composites (50 wt % BF).

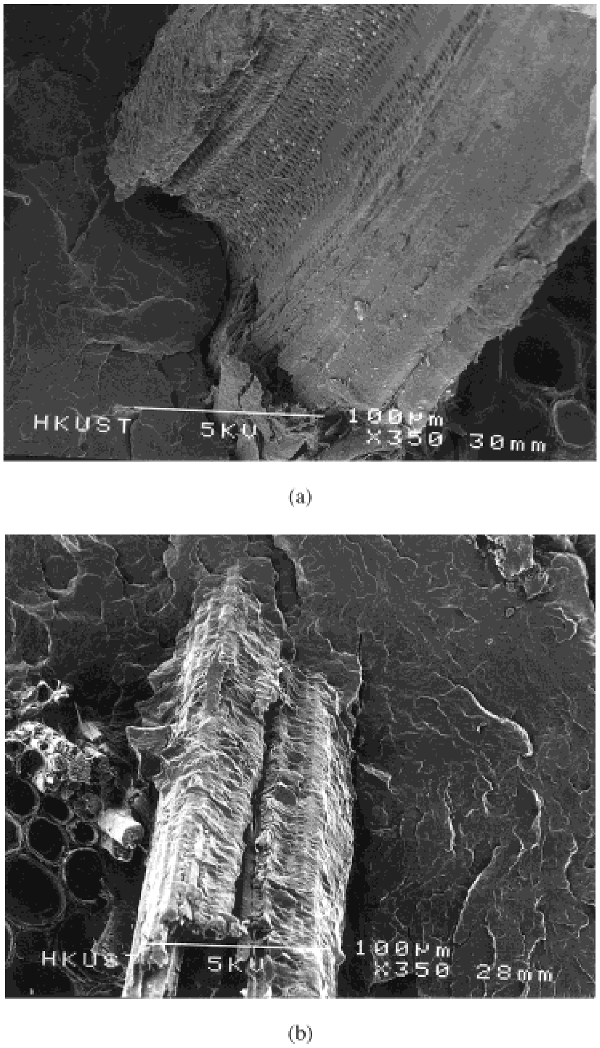


Figure 8 (a) The SEM photograph of the BFRP composite with the nonmodified PP as the matrix, which shows that the fiber is not wet by PP. (b) The SEM photograph of the BFRP composite with the maleated PP as the matrix, which shows that the fiber is completely wet by MAPP.

and bamboo fiber. As a result, the mechanical properties of the composites are enhanced.

Interfacial Adhesion of BFRP Composites

SEM photomicrographs of the fracture surfaces of the composites are shown in Figures 8(a) to 10(b). Figures 8(a) and 9(a) clearly show that there is no wetting on the surface of bamboo fiber by nonmodified PP, which is due to the fact that the surface energies between the fibers and the PP matrix are significantly different, knowing that the bamboo surface is hydrophilic and the PP surface is hydrophobic.[14,15] On contrary, Figures 8(b) and 9(b) show that, by adding MAPP to polymer matrix, the fiber surface is completely wet by the PP/MAPP matrix.

Referring to Figures 9(a) and (b), one can find, on the one hand, that bamboo fiber is not in close contact with the the PP matrix in Figure 9(a); on the other hand, the PP/MAPP matrix and bamboo fiber are intimately bonded together as, shown in Figure 9(b). Another thing that needs to be

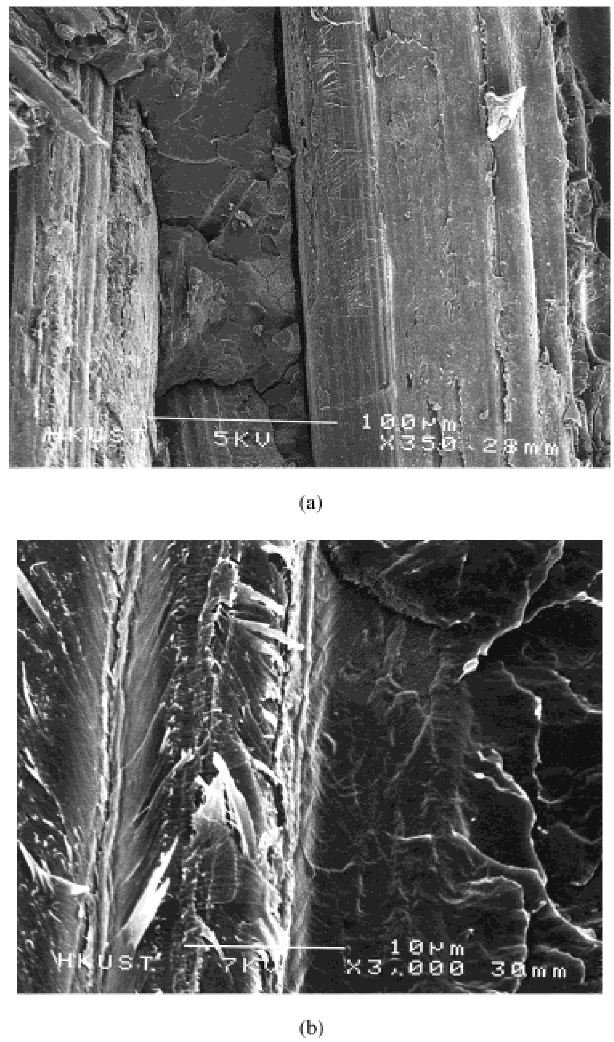
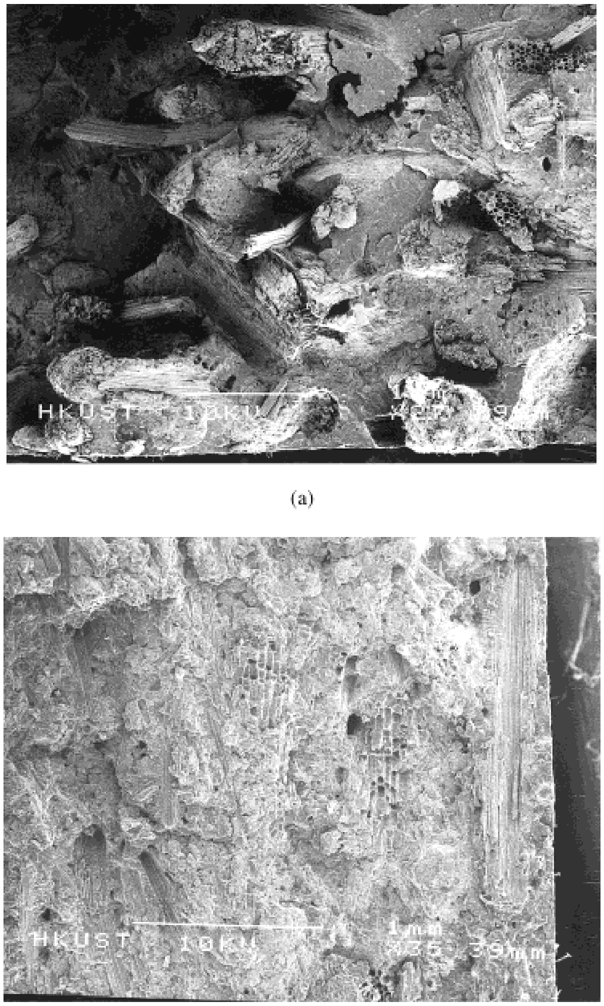


Figure 9 (a) The SEM photograph of the BFRP composite with the nonmodified PP as the matrix. The gap between fiber and polymer interfaces indicates poor adhesion between the two components. (b) The SEM photograph of the BFRP composite with the maleated PP as the matrix, and it is found that polymer and fiber are intimately bonded.



(a)

(b)

Figure 10 (a) The SEM photograph of the BFRP composite with the nonmodified PP as the matrix showing poor fiber distribution. (b) The SEM photograph of the BFRP composite with the maleated PP as the matrix showing better fiber distribution.

pointed out is that the magnification of Figure 9(b) is about 10 times that of Figure 9(a).

It is well known that, without effective wetting on the fiber, strong interfacial adhesion cannot be achieved, and the lack of interfacial interactions results in poor mechanical properties for the composites. Therefore, the SEM studies support the tensile and impact testing results discussed in the previous section. Moreover, with the enhanced interactions between the reinforcement and the matrix, fiber distribution becomes more uniform in the matrix. It is then shown in Figure 10(a) a poor distribution of bamboo fiber in the PP matrix, and in Figure 10(b) a better distribution of bamboo fiber in the PP/MAPP matrix.

The interaction between the bamboo fiber and PP/MAPP matrix can be attributed to the formation of hydrogen bonds in the interfacial region, for instance, between the hydroxyl (—OH) groups of cellulose or its counterpart lignin in bamboo fiber with the anhydride groups in the MAPP matrix. Furthermore, we found that MAPP can crystallize on the bamboo surface, so that the bamboo fiber acts as both a reinforcing agent and a nucleator for MAPP.[7] We believe that the surface crystallization also contributes to the better interface adhesion for the bamboo/PP/MAPP composite.

Effect of Bamboo Sizes

In this work, we selected four types of bamboo chips: (1) bamboo fiber sizes less than 500 μm; (2) 500–850 μm; (3) 850–1000 μm; and (4) 1000–2000 μm. Both PP and MAPP composites were employed to study the effect of bamboo size on the mechanical properties, while the bamboo concentration was kept approximately at 50 wt %. It is found, in Figures 11 and 12, that tensile modulus and tensile strength of PP and MAPP composites decrease as bamboo size increases. This is probably due to the fact that, at the same composition, a smaller fiber has a relatively larger surface area,

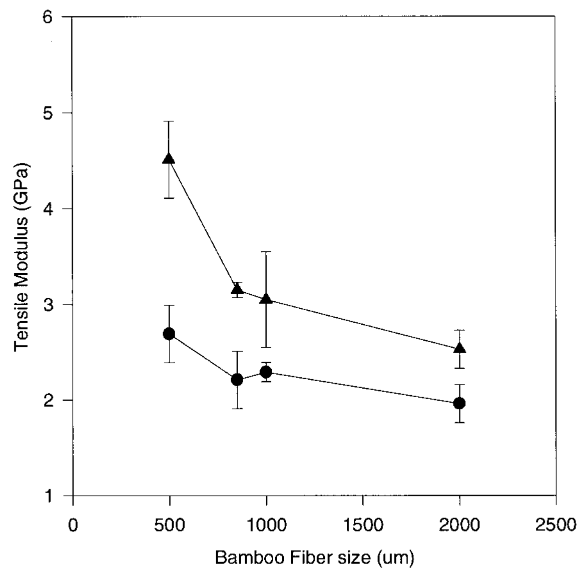


Figure 11 Effect of the size of bamboo fiber on the tensile modulus of BFRP composites (50 wt % BF): ● BF/PP composited; ▲ BF/MAPP composites.

which results in better contact between the fiber and the matrix.

Comparison with Commercial Wood Pulp Composite

As one of the objectives of this study was to develop a wood substitute potentially feasible for furniture industries, we compared the mechanical properties of the present BFRP composites with those of a commercial wood pulp composite that is now widely used in making office furniture. Figure 13 shows that the tensile strength and the stiffness of bamboo fiber-reinforced PP composites are all higher than those of the commercial wood pulp composite, and the tensile strength of the PP/MAPP composites is more than three times higher than that of the commercial wood pulp. This indicates that the new composites have a great potential in application as a new wood substitute.

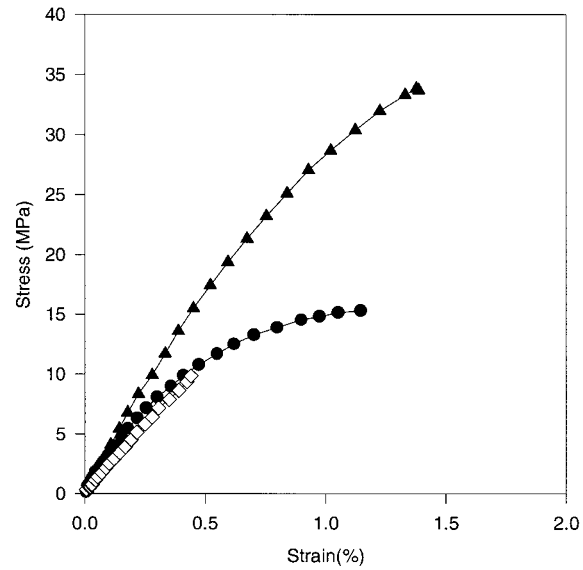


Figure 13 Comparison of the mechanical strength between the BFRP composites with a commercial product (50 wt %BF): ● BF/PP; ■ BF/m-MAPP; ◇ commercial wood pulp.

CONCLUSION

The MAPP can induce a better distribution of bamboo fiber of 50 to 60 wt % in the PP/MAPP matrix without any difficulty. The maximum values of the tensile strength (32–36 MPa) and the tensile modulus (5–6 GPa) were obtained at about 50 wt % bamboo content. Compared to the commercial wood pulp composite, the bamboo fiber-reinforced MAPP composite demonstrated higher tensile strength, lower density (0.920), and lower cost. Moreover, bamboo is renewable, which has a special environmental impact, and which may lead the new composite to a potential application as a new wood substitute.

In conjunction with our former study, it is also suggested that the MAPP crystallises on the bamboo surface, while PP cannot. It is, therefore, speculated that the intimate bonding between bamboo and the maleated PP matrix may be partially due to the crystallization effect, and partially due to the hydrogen bonding effect. As a result, the function of bamboo fiber is multiple, namely, as a reinforcer for the composite and as a nucleator for MAPP.[7]

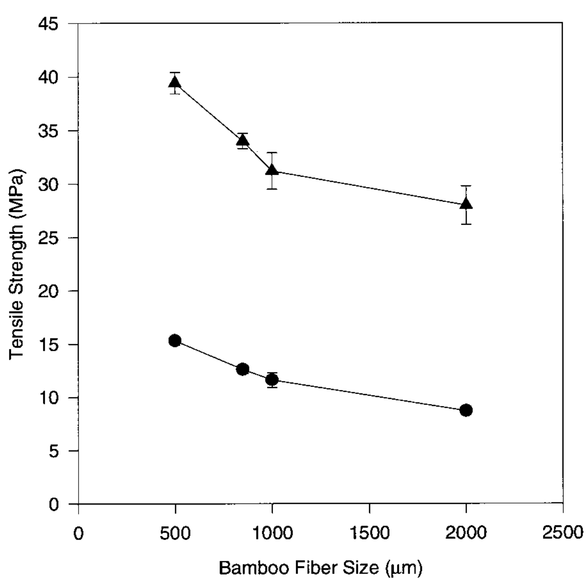


Figure 12 Effect of the size of bamboo fiber on the tensile strength off BFRP composites (50 wt % BF): ● BF/PP composites; ▲ BF/MAPP composites.

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