Development of bamboo-based polymer composites and their mechanical properties

Kazuya Okubo*, Toru Fujii, Yuzo Yamamoto

Department of Mechanical Engineering and Systems, Room YM304, Doshisha University, Kyotanabe 610-0321, Japan

Abstract

This paper presents the development of composites for ecological purposes (Eco-composites) using bamboo fibers and their basic mechanical properties. The steam explosion technique was applied to extract bamboo fibers from raw bamboo trees. The experimental results showed that the bamboo fibers (bundles) had a sufficient specific strength, which is equivalent to that of conventional glass fibers. The tensile strength and modulus of PP based composites using steam-exploded fibers increased about 15 and 30%, respectively, due to well impregnation and the reduction of the number of voids, compared to the composite using fibers that are mechanically extracted. The steam explosion technique is an effective method to extract bamboo fibers for reinforcing thermoplastics.

Keywords: A. Fibres; A. Polymer-matrix composites (PMCs); B. Strength; Bamboo

1. Introduction

Polymer-matrix composites, such as carbon or glass fiber reinforced plastics (CFRP/GFRP) have been widely used in industry since they have high strength and modulus. In fact, the total amount of consumption of GFRP was about 382 thousand tons in Japan in 2001. When the thermo-setting resins are used as a matrix, it is usually difficult to recycle the material. The thermoplastics are also unpractical to recycle due to high cost and low quality issues in the present state. Wasted FRPs are almost dumped although they do not decompose itself naturally in the ground, while others are burned. In recent years, a serious problem has come up in the use of plastics; especially for the polymer composite materials. Energy recycling systems are also under development using polymer composites as solid fuel. However, the glass fibers in the composites reduce the net heat and might damage the furnace, if their composites are burned in it as a solid fuel. It introduces another problems such as the disposal of the remains, because the glass fibers in the composite would also remain in the incinerator.

For the past several years, public attention has gone to natural fibers as a resource due to their fast growth. Bamboo is an abundant natural resource in Asia and South America, because it takes only several months to grow up. It has been traditionally used to construct various living facilities and tools [1]. The high strength with respect to its weight is derived from fibers longitudinally aligned in its body. Therefore, bamboo fibers are often called ‘natural glass fiber’. To practically apply the benefit of bamboo fibers, it is necessary to develop a process to fabricate bamboo composites as well as to extract qualitatively controlled fibers from bamboo trees.

However, it is difficult to extract bamboo fibers having its superior mechanical properties. The bamboo fiber is often brittle compared with other natural fibers, because the fibers are covered with lignin. Therefore, a devised process should be adopted to extract the bamboo fibers for reinforcement of composite materials. Several papers have already been published on the study of bamboo fiber reinforced composites using thermostetting plastic (epoxy and polyester) [2–6]. S. Jain et al. [2,3] showed the tensile, bending and static strength of the composite reinforced by bamboo orthogonal strip mats. A.V. Rajulu et al. [4] investigated the effect of fiber length on the tensile properties of short bamboo fiber epoxy composites. The bamboo/aluminium composites were also studied using reformed bamboo by S.H. Li et al. [5]. In particular, X. Chen et al. tested the mechanical properties of bamboo fiber-reinforced polypropylene and compared with those of commercial wood pulp [6], and M.M. Thwe et al. [7] investigated the effect of environmental actual aging on the mechanical properties of bamboo-glass fiber.
reinforced polymer matrix hybrid composites. However, few reports have discussed the practical fabrication process of bamboo fiber and its composite.

This paper proposes the benefit of the use of steam explosion technique in fabrication of the Bamboo Fiber Eco-Composites (BFEC) for ecological purposes. Firstly, superior mechanical properties of bamboo fiber were discussed in use of reinforcement of polymer matrix. Composites using some kinds of bamboo fibers were fabricated with the conventional hot-press method. Finally, their static strength and internal state after the fabrication were evaluated.

2. Materials

2.1. Bamboo fibers

Fig. 1(a) and (b) show a cross-section of bamboo. The bamboo column consists of many vascular bundles and xylem. A vascular bundle includes four sheaths of fibers, two vessels and some sieve tubes. Xylem surrounds each vascular bundle. The sheath consists of many single fibers whose diameter is 10–20 μm each in average. The chemical constituents of bamboo are primary cellulose, hemicellulose and lignin [2]. This reference also explains that cellulose composes most of the fiber and lignin is the second abundant chemical constituent of bamboo. All lignocellulosic based natural fibers consist of cellulose microfibrils in an amorphous matrix of lignin and hemicellulose. In Table 1, chemical constituents, density and microfibrillar angle of a few plant species are listed. The bamboo has 60% cellulose and a considerably high percentage of lignin (about 32%) [2].

In this study, fiber bundles of 125–210 μm in diameter (Fig. 2) were obtained by a sifter machine with mesh filtering the commercial bamboo chips.

2.2. Maleic anhydride polypropylene

Polypropylene (PP) can be effectively modified by maleic anhydride because maleic anhydride provides polar interactions and covalently link PP to the hydroxyl groups on the cellulose fiber [6,8–10]. In this study, MAPP (maleic anhydride modified PP, (Umex 1001: Sanyo Chemical Industries, Ltd)/PP (Novatec; Japan Polychem Co.) mixed at a ratio of 5/95 in weight) was used as a matrix of BFEC.

3. Experimental and fabricating method

3.1. Tensile test of bamboo fiber bundle

First of all, the basic components of bamboo fiber bundle were investigated in order to determine its specific properties. The average diameters of fiber bundles were measured in microscope (the number of observations was about 100), while their densities were referred in the published papers [2,11] as listed in Table 2.

Fig. 3 shows the dimensions of the fiber bundle specimen. Before the test, fiber bundles were dried for 2 h at 120 °C. Then one of the bamboo fiber bundles was glued on a sheet of paper. The paper works as an attachment for the specimen. Then, the gage positions of the paper were cut after chucking it on the testing machine to apply the tensile load. Tensile tests were conducted using a small-capacity testing machine (ASG-H/Ez Test-500: shimadzu) at 1 mm/min of crosshead speed. The reaction force and displacement of the chuck were monitored with connected PC, and nominal stress and strain were determined while the tensile load.

<table>
<thead>
<tr>
<th>Types of fiber</th>
<th>Microfibril angle (deg)</th>
<th>Cellulose (%)</th>
<th>Lignin (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coir</td>
<td>30–49</td>
<td>43</td>
<td>45</td>
</tr>
<tr>
<td>Banana</td>
<td>11</td>
<td>65</td>
<td>5</td>
</tr>
<tr>
<td>Sisal</td>
<td>20–25</td>
<td>70</td>
<td>12</td>
</tr>
<tr>
<td>Jute</td>
<td>8.1</td>
<td>63</td>
<td>11.7</td>
</tr>
<tr>
<td>Bamboo</td>
<td>2–10</td>
<td>60.8</td>
<td>32.2</td>
</tr>
</tbody>
</table>

Fig. 1. Cross-section of bamboo tree.

Fig. 2. Bamboo fiber bundles selected by shifter machine.
was being loaded to the specimen at laboratory condition. Their modulus was also estimated by the responses of nominal stress and strain. In this experiment, jute fibers were also tested under the same condition, in order to compare their mechanical properties with those of bamboo fibers.

3.2. Molding process of BFEC

It is known that the interfacial adhesion between matrix and a fiber is degraded due to water absorption [12]. To remove moisture, the bamboo fiber bundles were dried for 3 h at 120 °C in a drying machine. During the process of fabricating BFEC, thin films of the MAPP/PP and the bamboo fiber bundles scattered at random were alternatively stacked. Then, they were hot-pressed at 190 °C under 2 MPa for 30 min. The weight content and the volume fraction of bamboo fiber bundle were about 51 and 41%, respectively, as a controlling condition. After the molding process, a 150 × 150 × 2 mm thick plate of BFEC was obtained.

3.3. Tensile test of BFEC

Tensile specimens of the BFEC were cut off in the form of rectangular strips from the molded plate. Fig. 4 shows dimensions of the BFEC specimens. The most of the dimensions of the specimen followed some standards, but they did not completely fit ASTM. Seven samples of BFEC were tested on a universal testing machine (AUTOGRAPH: Shimadzu Co.) at 1 mm/min of crosshead speed. Stress–strain curves were generated for each sample. To evaluate the impregnation state of resin into the bamboo fiber bundles, polished surfaces of the specimen were observed by optical microscope. The fractured surfaces were also checked by the scanning electron microscope (SEM).

4. Results and discussion

4.1. Strength distribution of bamboo fiber bundle

Fig. 5 shows the distributions of tensile strength of the bamboo fiber bundles and the jute fibers. Their mechanical properties are listed in Table 2. This table also indicates

<table>
<thead>
<tr>
<th>Types of fiber</th>
<th>Physical properties</th>
<th>Mechanical properties</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Diameter (g/m³)</td>
<td>Tensile strength (MPa)</td>
</tr>
<tr>
<td>Bundle of bamboo</td>
<td>800 b</td>
<td>441 220</td>
</tr>
<tr>
<td>Jute</td>
<td>1300 c</td>
<td>370 145</td>
</tr>
<tr>
<td>E-glassd</td>
<td>2500 –</td>
<td>2400 –</td>
</tr>
</tbody>
</table>

* The number of observations was about 100.
* Density of bamboo bundle is referred to Ref. [2].
* Density of jute is calculated from the specific gravity referred to Ref. [11].
* The data of E-glass is referred to Ref. [12].

Fig. 5. Strength distribution of the bamboo fiber bundles and jute fibres.

Table 2

Mechanical properties of bamboo, jute and E-glass fibers

<table>
<thead>
<tr>
<th>Types of fiber</th>
<th>Physical properties</th>
<th>Mechanical properties</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Diameter (µm)</td>
<td>Tensile strength (MPa)</td>
</tr>
<tr>
<td>Bundle of bamboo</td>
<td>88–125</td>
<td>441 220</td>
</tr>
<tr>
<td>Jute</td>
<td>30.0–50.0</td>
<td>370 145</td>
</tr>
<tr>
<td>E-glassd</td>
<td>2500</td>
<td>2400</td>
</tr>
</tbody>
</table>

a The number of observations was about 100.
b Density of bamboo bundle is referred to Ref. [2].
c Density of jute is calculated from the specific gravity referred to Ref. [11].
d The data of E-glass is referred to Ref. [12].
typical mechanical properties of E-glass fiber [13]. The tensile strength of bamboo fiber bundle is as high as that of jute fiber. The densities of these natural fibers are remarkably lower than that of E-glass fiber. As a result, the bamboo fiber has a particularly high specific strength.

4.2. Tensile strength of BFEC

Fig. 6 shows a typical tensile stress–strain response of the BFEC using mechanically extracted bamboo fiber bundles. It was found that the elastic modulus of BFEC increased about 2.6 times higher than that of neat MAPP/PP. Fig. 7 shows the cumulative probability of BFEC with respect to tensile strength. A bold solid line in this figure indicates the average strength of the neat MAPP/PP sample. It was confirmed that the tensile strength of BFEC was 1.36 times higher than that of the neat MAPP/PP.

It can be said that the bamboo fiber bundles works as reinforcement in BFEC. However, the strength of BFEC was not high enough for actual uses if the bamboo composite was fabricated using mechanically extracted bamboo fiber bundles.

4.3. Resin impregnating state

Fig. 8 shows a typical impregnation state of resin into randomly aligned bamboo fiber bundles in BFEC. Many voids exist around the fibers. The fractured surface of the specimen is shown in Fig. 9. The SEM photograph of the fractured surface indicates poor adhesion between bamboo fibers and the matrix. Large spaces were also found at the points where the fiber bundles were crossing. It can be assumed that when the bamboo fiber bundles are stacked on top of each other, the spaces are likely to be made at the crossover points because of their rigidity. The impregnation...
of MAPP/PP into those spaces was insufficient to fabricate the applicable BFEC due to its high viscosity.

To reduce the number of voids in BFEC, it is necessary to decrease the diameter of fiber bundles by dividing them into single fibers. The test results showed that the previous processes were not effective, so the new method should be introduced.

4.4. Applying steam explosion method

In this study, the steam explosion technique was applied to extract fibers from bamboo tree. The steam explosion technique has been known as an effective method to separate the lignin from the woody materials [14,15].

Fig. 10 shows the SEM photograph of a surface of bamboo fiber bundle extracted by the steam explosion technique. Table 3 lists the conditions of the steam explosion in this study. This photograph indicates that the bundles were not effectively separated into single fibers and a large amount of lignin remained on the surface of the bundle even after the steam explosion was applied. Therefore, this study proposed additional process of mechanically rubbing bundles in addition to the steam explosion for their further separation.

Fig. 11 shows the SEM photograph of the bamboo fiber bundles after this method was applied using a mixing machine. These fibers appeared as cotton fibers, which can be referred to as Bamboo Fiber Cotton (BFc). The diameter of BFc was reduced to 10–30 µm and lignin was almost removed from the surface of fibers.

A typical tensile stress–strain curve and the tensile strength distribution of improved BFEC using Bamboo Fiber Cotton Eco-Composite (BFcEC) and conventional BFEC are shown in Figs. 12 and 13, respectively. Table 4 also shows the average ultimate strength and Young’s modulus of BFEC, BFcEC and MAPP/PP. Both the tensile strength and Young’s modulus of the BFcEC increased about 15 and 30%, respectively, in comparison with the conventional BFEC. Fig. 14 shows the impregnation state of resin into the BFc in the BFcEC. This photograph demonstrates the improved state of the BFcEC with drastically decreased number and size of voids.

Table 3

<table>
<thead>
<tr>
<th>Contents</th>
<th>Time (min)</th>
<th>Temperature (°C)</th>
<th>Pressure (MPa)</th>
<th>The number of times</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bamboo</td>
<td>100</td>
<td>170</td>
<td>0.8</td>
<td>8</td>
</tr>
</tbody>
</table>

Fig. 10. Surface of the extracted bamboo fiber bundle using the steam explosion method.

Fig. 11. Surface of rubbed bamboo fibers.

Fig. 12. Stress–strain curves of BFcEC and BFEC.

Fig. 14. Impregnation state of resin into the BFc in the BFcEC.
Fig. 15 indicates the average tensile strength of the improved BFcEC and conventional BFEC when the weight content of bamboo fiber was changed to 40 and 60% from the controlled condition of 51%. At the higher weight content, an increase in the tensile strength was observed when the BFc was used as the reinforcement of the composite. This means that high weight content of BFc enables the bamboo composites to increase their strength in the most effective way, when the bamboo fiber is modified into the ‘cotton shape’.

This study found that the steam explosion technique is essential to extract the bamboo fibers. In addition, it is necessary to mechanically modify the bamboo fiber bundles into the ‘cotton shape’ after the steam explosion process, for the bamboo to function as reinforcement of plastics.

5. Conclusion

1. Bamboo fiber bundles have a potential ability to work as the reinforcement of polymer matrix. The tensile strength of the bamboo fiber bundle is as high as that of jute fiber.
2. Both the tensile strength and Young’s modulus of the improved BFcEC increased about 15 and 30%, respectively, in comparison with the conventional BFEC.
3. The impregnation state of the improved BFcEC drastically decreased the number and size of voids.
4. High weight content of bamboo fiber enables the bamboo composites to increase their strength in the most effective way, when the bamboo fiber is modified into the ‘cotton shape’.
5. The bamboo fiber bundles need to be mechanically modified into the ‘cotton shape’ after the steam explosion method is applied, in order to benefit from bamboo fiber’s potential function as reinforcement of plastics.

Acknowledgements

This research is partially supported by a grant from the Ministry of Education and Science, Japan to the research project at Doshisha University, which is named ‘Development of functional bamboo fibers and their eco-composites’. SANYO CHEMICAL INDUSTRYIES, Ltd supplied...
Maleic anhydride Polypropylene. Mr SHITO (graduate students of Doshisha University) conducted necessary experiments and investigations to obtain the results.

References
