Effect of Fiber Length on Mechanical Properties of "Green" Composites Using a Starch-Based Resin and Short Bamboo Fibers*

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This paper describes a method to fabricate short bamboo fiber reinforced "green" composites (BFGC) and evaluate their mechanical properties. The composites were prepared by hot-pressing a mixture of starch-based resin and short bamboo fibers. Their tensile strength and flexural strength were characterized. The effects of fiber content and fiber length on the mechanical properties of BFGC were investigated in detail. Both tensile and flexural strengths of BFGC were strongly affected by fiber aspect ratio and fiber content. Bamboo fibers with a small aspect ratio of 20 do not act as reinforcement but as filler.

Key Words: Composite Material, Reinforced Plastics, Tensile Properties, Law of Mixture, Bamboo Fiber, "Green" Composites, Biodegradable Resin, Bio-Composites, Eco-Materials

1. Introduction

At the present time biodegradable resins receive considerable attention as earth-conscious materials (eco-materials) and have been recognized as materials with a small environmental load, because biodegradable resins may be resolved in both water and carbon dioxide after perfect biodegradation by the action of microorganisms. Because almost all of the biodegradable resins have relatively low strength, which is equivalent to the strength of a general-purpose polymer such as polypropylene or polyethylene, it is impossible for biodegradable resins to be used as high strength structural components. Therefore, research on strengthening biodegradable resins has been carried out by combining them with strong natural fibers[1] such as ramie[2], hemp[3],[4], pineapple[5],[6], henequen[7] and bamboo[8],[9].

Bamboo fiber is recognized as one of the most attractive candidates as a strengthening natural fiber[10],[11]. It has several advantages, such as (1) the environmental load is small, because it is renewable yearly and it grows rapidly, thus it is easy to regenerate after cutting, and (2) the bamboo fiber has relatively high strength compared with other natural fibers such as jute and cotton. Added to these advantages, bamboo is typical of unutilized natural bio-resources; therefore, we have carried out research on bamboo fibers and bamboo fiber-reinforced composites.

In this study, the investigations of the effects of fiber content and fiber length on mechanical properties of bamboo fiber reinforced "green" composites (BFGC) have been carried out.

2. Experimental Methods

2.1 Sample preparation

An emulsion-type starch-based biodegradable resin (CP-300, Miyoshi Oil & Fat) was used as the matrix resin. Fine biodegradable resin particles approximately 6 μm in diameter are dispersed in a water-based solution of pH 5.0. The representative physical properties of this biodegradable resin are listed in Table 1.

Bamboo fibers as a reinforcement material were obtained by steam explosion[11]. Reinforcing short fibers 200 μm in diameter were prepared from the bamboo fibers chopped in a predetermined length from 4 to 25 mm. First, short bamboo fibers were scattered on a water-diluted emulsion of biodegradable resin poured in a shallow plate. Randomness of the fiber orientation was achieved by allowing the fibers to fall freely. Secondly, this mixture was dried in an oven at 105°C for two hours to obtain a preformed sheet. Finally, several preformed sheets were

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stacked and hot-pressed at 130°C under a constant pressure of 20 MPa for 5 min.

Several BFGC specimens were fabricated with alkali treated bamboo fibers, because alkali treatment has been recognized as an effective surface modification method compared with other methods such as acetylation and plasma treatment. The surface of the bamboo fiber was alkali-treated using an aqueous solution of 0.25 mol/L sodium hydroxide. This alkali treatment was carried out at room temperature for 30 min. After alkali treatment, the fiber was washed in distilled water in several times. Figure 1 shows photographs of untreated and alkali-treated bamboo fibers. It can be seen that contamination attached to the surface is removed by alkali treatment.

Table 1 Properties of biodegradable resin used as matrix.

Density (g/cm³)	**1.18**
Water absorption (%)	**2.0**
Tensile strength (MPa)	**12.2**
Tensile elongation (%)	**550**
Young's modulus (MPa)	**431**
Flexural strength (MPa)	**13.3**
Flexural modulus (MPa)	**460**

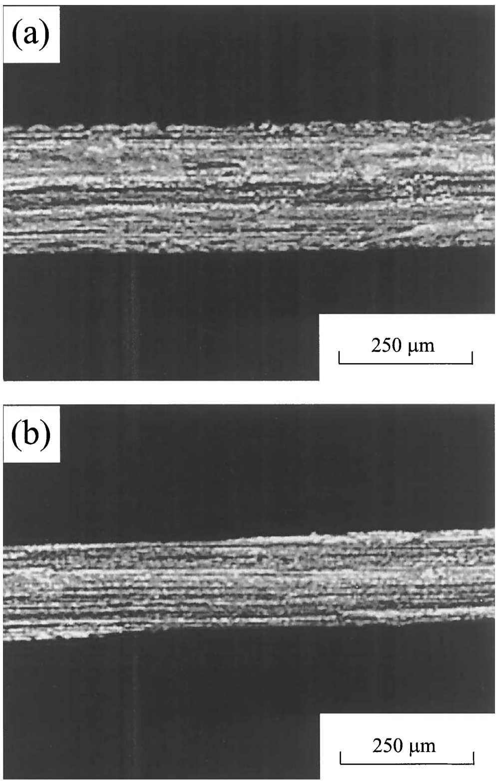

Fig. 1 Photomicrographs of (a) untreated bamboo fiber and (b) alkali-treated bamboo fiber.

2. 2 Mechanical testing and observation

Both tensile tests and flexural tests were carried out using an Instron universal test machine (Model 5567) to evaluate the mechanical properties of "green" composites reinforced with randomly oriented bamboo fibers. The flexural strength was measured using a 3-point bending test with a span length of 50 mm and a crosshead speed of 1.0 mm/min. Shapes of specimens for flexural tests were 100 mm in length, 15 mm in width and 1.5 mm in thickness. The tensile test was also carried out at a crosshead speed of 1.0 mm/min. The specimen configuration for tensile tests was 100 mm in length, 10 mm in width, 1.5 mm in thickness, with a gage length of 30 mm. In addition, 2 mm thick aluminum tabs were glued at both ends of the tensile specimen to prevent damage introduced during fixing. In this study, the tensile fracture surfaces of the BFGC samples were examined using an optical microscope and a scanning electron microscope (SEM).

3. Experimental Results and Discussions

3. 1 The effect of fiber length on mechanical properties of BFGC

The effect of fiber length on tensile strength and 3-point flexural strength of BFGC are shown in Figs. 2 and 3, respectively. Both figures show similar dependence on

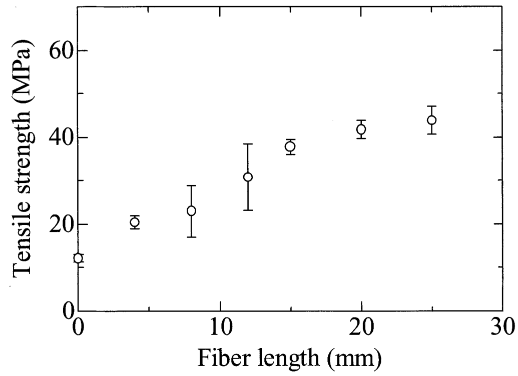

Fig. 2 Relationship between tensile strength of BFGC and fiber length. The fiber content is 50 mass %.

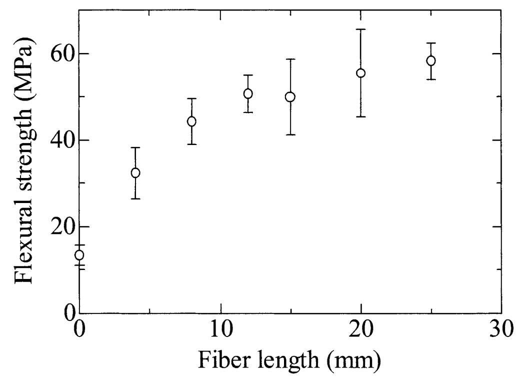

Fig. 3 Relationship between flexural strength of BFGC and fiber length. The fiber content is 50 mass %.

fiber length. In the region in which the fiber length is less than 15 mm, both tensile strength and flexural strength of BFGC increase with increasing fiber length. This increasing tendency in tensile strength, however, decreases with increasing fiber length in the region in which fiber length exceeds 15 mm.

The relationship between tensile failure stress of randomly oriented fiber composites, σ_c and fiber length L is expressed in the following[12]:

$$\sigma_c = \sigma_f C F(L) V_f + \sigma_m (1 - V_f), \quad (1)$$

where V_f is the fiber volume fraction, σ_f is the tensile strength of fiber, and σ_m is the matrix stress at the onset of fiber fracture. C is a coefficient related to fiber orientation. The value of C varies such that $C = 1$ for unidirectional fiber orientation and $C = 1/3$ for two-dimensional random orientation. The symbol $F(L)$ is a function of the fiber length L, and is given by the following equations:

$$F(L) = L/(2L_c) \quad L < L_c \quad (2)$$

$$F(L) = 1 - L_c/(2L) \quad L \geq L_c \quad (3)$$

where L_c is the critical fiber length. It is obvious that the value of $F(L)$ equals unity in the case of $L \to \infty$ and that $F(L) = 0.5$ in the case of $L = L_c$.

The first point to be discussed is the applicability of Eq. (1) to BFGC. Although bamboo fiber is composed of many fine fibers approximately 20 μm in diameter, the bamboo fiber behaves as a single fiber during tensile deformation. In addition, Eq. (1) is derived from a force equilibrium condition, and this is independent of a sample's dimensions. The second point is the randomness of fiber orientation. As mentioned in section 2.1, the BFGCs were fabricated from several preformed sheets containing randomly oriented bamboo fibers. From surface observations of BFGC samples, there is no indication of the preferential fiber orientation. Consequently, we may say that Eq. (1) can be applied to the BFGCs.

In this study, a theoretical failure stress of the randomly oriented fiber composite is estimated as approximately 100 MPa, because fiber strength, σ_f is approximately 600 MPa[11] and fiber volume fraction, V_f is 48%. The experimental value of tensile strength for the composites reinforced with fibers 25 mm in length was only 45 MPa. This experimental value is almost half the theoretical strength calculated using $L_c = 30$ mm from Eq. (1) as shown in Fig. 4. The decrease in tensile strength compared with the theoretical value has been reported by many researchers, including Luo, et al.[5] and Lodha, et al.[13] The strength drop has been attributed to two situations: namely, the existence of defects, such as voids, and weak interface bonding between matrix and reinforcement. Therefore, part of the discrepancy in this study may also be attributed to low fiber/matrix interface adhesion strength. As shown in Fig. 4, the tensile strength of alkali-treated BFGC with $L = 25$ mm and a fiber content of 50 mass % increased to approximately 60 MPa. Although there is still a considerable difference between experimental strength and theoretical one, it can be seen from this graph that the fiber/matrix interface adhesion strength has a great influence on the mechanical properties of BFGC. Further study is required to determine the influence of the interfacial adhesion strength as well as void content on the mechanical properties of BFGC.

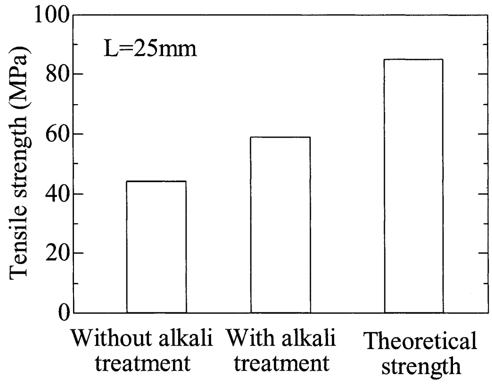

Fig. 4 The effect of alkali treatment on the tensile strength of BFGC with fiber length of 25 mm and fiber content of 50 mass %, and a comparison with theoretical strength calculated from Eq. (1).

The fracture surfaces of tensile specimens reinforced with fibers 8 mm and 15 mm in length are depicted in Figs. 5 and 6, respectively. Both micrographs show the existence of fiber pull-out on the fracture surfaces, which is indicative of weak interface bonding in these composites. We can see from Fig. 5 that almost all fibers were pulled-out without fiber fracture and that the specimen with 4 mm fibers had the same fracture surface morphology as the others. This indicates that a fiber length of 8 mm is less than the critical length for BFGC.

On the other hand, the fracture of fiber is confirmed in the specimen with 15 mm fibers (Fig. 6). This indicates that a fiber length of 15 mm is larger than the critical length for BFGC. The frequency of breakage in the pull-out fibers increased with increasing fiber length. It seems reasonable that the critical length of BFGC is approximately 12 mm and the corresponding aspect ratio is about 60.

3.2 The effect of fiber content on mechanical properties of BFGC

The relationships between tensile strength and 3-point flexural strength and fiber content are shown in Figs. 7 and 8, respectively. From both figures, it can be seen that both strengths increase with increasing of fiber content and that this increasing tendency becomes more pronounced with increasing fiber length. The tensile strength value of 21 MPa and the 3-point flexural strength value of 32 MPa for the 4 mm BFGC with a fiber content

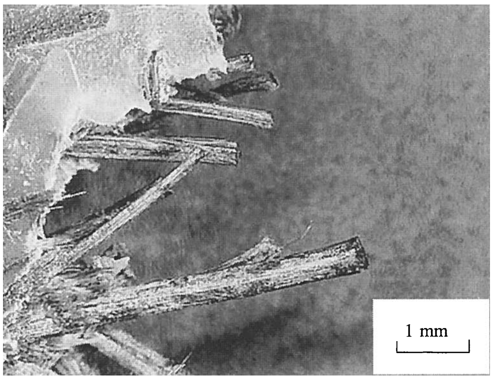

Fig. 5 Fracture surface of composites reinforced by short bamboo fibers 8 mm in length, showing pull-out fibers without fiber fracture.

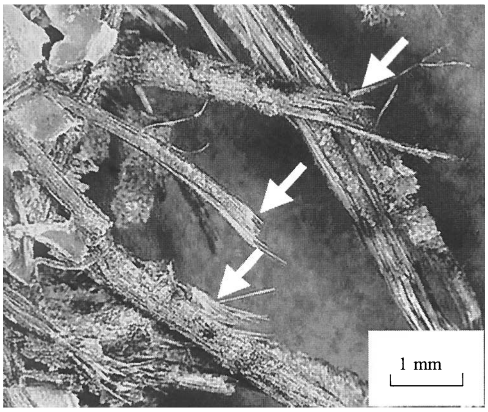

Fig. 6 Fracture surface of composites reinforced by short bamboo fibers 15 mm in length. Arrows show fiber fracture.

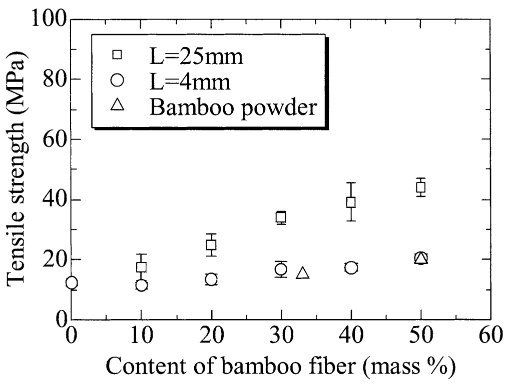

Fig. 7 Relationship between tensile strength of BFGC and content of bamboo fiber.

of 50 mass % are almost the same as those for "green" composites fabricated from the same starch-based resin and bamboo powder (50 mass % of bamboo powder / 50 mass % of resin), which are indicated by triangles (Δ) in Figs. 7 and 8[14]. In this comparison, the effect of void content on the mechanical properties of the BFGC seems to be negligible, because both samples were fabricated in the same manner, and thus both samples have similar void

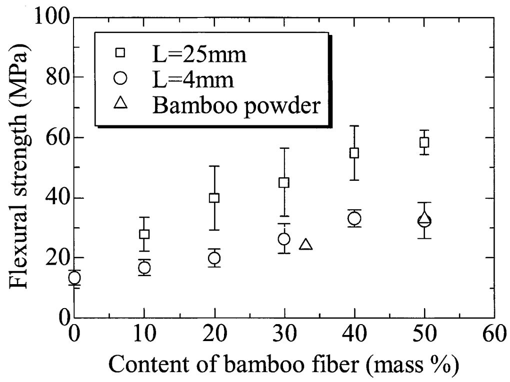

Fig. 8 Relationship between flexural strength of BFGC and content of bamboo fiber.

content. It should be noted that bamboo fibers with small aspect ratio (L/d) of 20 act as filler and do not act as reinforcement.

4. Conclusion

The mechanical properties of bamboo fiber-reinforced "green" composites (BFGC) were investigated. The major results obtained from this research are summarized briefly as follows:

(1) Both tensile strength and flexural strength are strongly affected by fiber length and fiber content. The trend in increasing strength is saturated for fiber lengths over 15 mm.

(2) The experimental value of tensile strength for the BFGC with 25 mm fibers is 45 MPa. This experimental value is almost half the theoretical strength. Part of this discrepancy is attributed to the fiber/matrix interface adhesion strength.

(3) In the BFGC, bamboo fibers with a small aspect ratio of 20 act as filler and do not act as reinforcement. The mechanical properties of BFGC are similar to those of the "green" composites made from bamboo powders and biodegradable resins.

Acknowledgement

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