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Strength evaluation of cross-ply green composite laminates reinforced by bamboo fiber

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ABSTRACT

Steam exploded bamboo (SEB) fibers were treated with alkali solution to remove lignin and hemicelluloses and also to increase the compatibility with biodegradable matrix resin. The fibers were processed by simple hand-lay-up method and hot pressed using dispersion-type biodegradable poly lactic acid (PLA) resin to produce a PLA/bamboo fiber cross-ply $(0/90)_s$ laminate composites, whose fiber content varied from 17 up to 68 wt.%. The intermolecular interaction among bamboo fiber and PLA matrix was discussed based on Fourier transform infrared (FTIR) analysis. The results showed that the tensile strength of alkali treated bamboo fiber was comparable with those of common strong natural fibers such as hemp and flax fibers. The composites' strength was similar to that of ordinary glass fiber-reinforced plastics laminate and the specific strength was three times higher than that of mild steel. It was also found that the cross-ply $(0/90)_s$ SEB/PLA laminate has the same cracking character as the common cross-ply laminates based on carbon or glass fibers.

1. Introduction

For the past several years, bamboo fiber has been considered as an important plant fiber and has enormous potential to be used as reinforcement in polymer composites. Its characteristics, mechanical properties, thermal properties, and effective extraction by steam explosion method for reinforcing thermoplastics had made it a useful material for applying in composites [1–5]. On the basis of earlier reports, bamboo fiber has 60% cellulose with high content of lignin and relatively small microfibril angle (2–10°), which is one of the major factors for its high tensile strength [6]. These characteristic properties have made bamboo fiber a choice for reinforcement in a variety of matrices [7].

Some studies were carried out on the mechanical properties of bamboo fiber. Nogata and Takahashi [1] evaluated the tensile strength of the bamboo fiber to be in the range of 350–900 MPa. Amada et al. [2] investigated the tensile strength of the bamboo column at several locations along the height, as a function of the radial distance. They reported that tensile strength and Young's modulus varied from 100 to 600 MPa and from 3 to 15 GPa, respectively. Trujillo et al. [5] inspected the average of the bamboo fiber strength as a function of different scale variables: fiber length, fiber surface area and fiber volume. They confirmed that the average fiber strength varied from 733 MPa to 943 MPa.

A variety of methods have been developed by researchers to extract bamboo fibers from bamboo column. Sodium hydroxide (NaOH) or alkaline treatment and steam explosion were reported to be effective to improve the mechanical properties of bamboo fibers [4,8]. These treatments were used as a tool to facilitate bamboo fiber extraction by optimizing the separation of fibers. The steam explosion method followed by mechanical treatment has been attractive as an effective pre-treatment for depolymerization of lignin in plant biomass [9–12]. Lignin is used for binding cellulose microfibrils to form a composite structure and also known to resist microbial degradation. Although lignin is thermally stable, it is considered to be responsible for the anti-UV degradation of the fiber [13]. The steam explosion process partially removes the lignin from the middle lamella of fiber bundles while retaining the lignin on fibers' surface. As a result, extracted fibers may not have strong hydrophilic character owing to the hydrophobic character of lignin. Hence, steam hydrolyzed solids are expected to have an improved compatibility with usually hydrophobic polymer matrices or other thermoset or thermoplastic matrices. Zakikhani et al. [4] reported that the tensile strength of bamboo fibers extracted by steam-explosion varied from 300 to 862 MPa.

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Several papers have already reported on the study of bamboo fiber-reinforced composites using thermosetting resins such as epoxy and polyester [14–17]. Jain et al. [14] investigated the tensile, flexural, and impact strengths and the fracture mechanism of composites reinforced by bamboo fiber mat and orthogonal strip mat. Kushwaha et al. [15] showed that the tensile strength of alkali-treated bamboo-reinforced epoxy was higher than that of composites reinforced by mercerized fibers treated with silane. Verma and Chariar [16,17] tested the mechanical properties of layered bamboo-epoxy composite laminates. Very few reports on the evaluation of bamboo biodegradable composites based on laminates exist in the literature [18] and their mechanical properties are still lower than that of conventional glass fiber-reinforced composites.

PLA is a versatile thermoplastic polymer derived from lactic acid made from the fermentation of sugarcanes, sugar beets, corn, potato, and other starch-rich products. Its production requires less energy, less water and entails less carbon dioxide release than traditional petroleum-based polymers [19,20] with the advantages of compostability and degradability, favorable melting point (160–180 °C) to be used with natural fibers, versatility with many applications in a variety of industrial fields, and processability by extrusion, injection molding, thermoforming, and compression molding [21]. There are some studies in the literature concerned with the development of green composites based on bamboo fiber and PLA resin composites [8,21–23], most of them using short bamboo fibers as reinforcement. There are no studies developing cross-ply laminate composites using steam exploded bamboo (SEB) fibers and biodegradable resin, exploiting the benefits of the characteristics of long fibers to manufacture composites for structural or semi-structural applications.

This paper investigates the advantages of the use of steam-exploded bamboo fiber in the fabrication of bamboo fiber-reinforced biodegradable PLA resin $(0/90)_s$ in cross-ply laminate composites. The strength behavior of the composites was characterized in order to find the appropriate conditions from the viewpoint of mechanical performance of the composites, including tensile strength, strain at failure, and Young's modulus. Morphological analyses were performed using a digital microscope and a scanning electron microscope (SEM) to observe the failure mode of cross-ply laminates. Examinations through Fourier transform infrared (FTIR) spectroscopy were also conducted to investigate the chemical compounds of the fibers and resin. It was found that the tensile strength of the composite was comparable to that of ordinary glass fiber-reinforced plastics. It was also noticed that the specific strength of the composite was 3 times as high as that of mild steel. The bamboo-PLA composites can substitute common glass fiber-reinforced composites for non-structural and semi-structural applications such as door trim panels, load floor, and luggage compartment floor of interior parts in automobiles.

2. Materials and method

2.1. Matrix resin

A dispersion-type PLA resin (Miyoshi Oil & Fat Co., Ltd.; PL-2000) was used as the matrix resin. This resin contains fine particles smaller than 5 μm in diameter, suspended in aqueous solution with a solid content of approximately 40 wt.%. Typical physical properties of this PLA resin are presented in Table 1.

Table 1
Properties of dispersion-type PL-2000 resin.

Density (kg/m^3)	1260
Tensile strength (MPa)	25–30
Strain at break (%)	1.8
Young's modulus (GPa)	2.34
Particle diameter (μm)	2.2

2.2. Bamboo fibers

The main chemical constituents of bamboo fiber are cellulose, hemicelluloses, and lignin. The approximate chemical composition of bamboo fiber is cellulose (60%) and a considerably high percentage of lignin (32%) [14].

In this study, *Moso* bamboo (5 years old) fibers were acquired from Ban Co. Ltd., Japan, which were obtained from bamboo column with internodal length of about 350 mm by a steam explosion method [23] and fibers with the diameter ranging from 200 to 300 μm were carefully selected.

2.3. Composite fabrication

A hand lay-up method was adopted to prepare the sheet layers. First, bamboo fibers were cut into 100 mm in length. The surface of the fibers was still covered with excess lignin. In order to remove it, bamboo fibers were treated with a 0.25 M NaOH solution at 30 °C for 30 min, then washed and rubbed in water, and finally dried at 105 °C for 5 h. Both fiber arrangement and fiber content are the most important factors affecting the properties of composites. In this study, the arrangement is limited to cross-ply orientation. The bamboo fibers were dipped into a PL-2000 suspension, dried at room temperature, and four sheets, each having 100 mm × 100 mm × 2 mm were arranged by aligning the bamboo fibers. The four sheet layers were prepared to form cross-ply $(0/90)_s$ orientations, stacked and hot-pressed at 165 °C under a constant pressure of 3 MPa for 10 min, resulting in cross-ply SEB/PLA composites as shown in Fig. 1.

The direction parallel to the loading direction, in tensile test measurement, was defined as 0°, so that 90° corresponded to the direction perpendicular to loading. The composite samples were prepared with seven different fiber contents for tensile test (17, 23, 36, 40, 50, 62, and 68 wt.%) with the density around 1.28 g/cm^3.

2.4. Characterization of fibers and composites

2.4.1. Fourier transform infrared (FTIR) spectroscopy

FTIR analysis of bamboo fibers and PL-2000 resin was carried out by using a Bio-Rad FTIR spectrometer model FTX 3000 MX

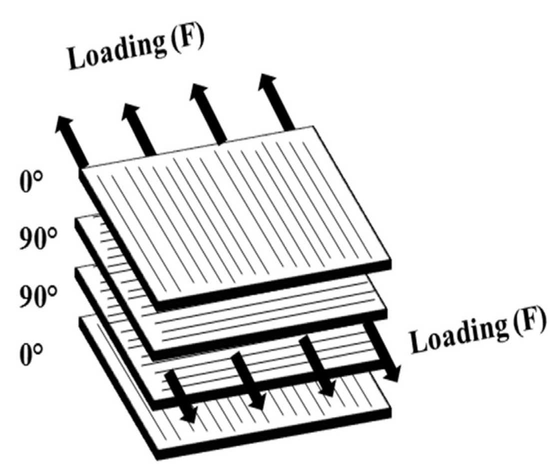

Fig. 1. Laminate sequence and loading direction of cross-ply SEB/PLA composites $(0/90)_s$.