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A novel process to improve yield and mechanical performance of bamboo fiber reinforced composite via mechanical treatments

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A B S T R A C T

The aims of the present study are to produce bamboo fiber reinforced composite (BFRC) with high yield and to investigate the mechanical properties of BFRC comparing with those of commercial bamboo scrimber (BS) and laminated bamboo lumber (LBL). A novel process was developed for production of BFRC using oriented bamboo fiber mat (OBFM) made by a pilot machine. The yield and the mechanical properties of BFRC were investigated and analyzed in comparing with those of raw bamboo and other bamboo-based composites. The results show that the novel process produces 92.54% yield of OBFM due to without any chemical and special removing of inner and outer layer of bamboo during processing. In addition, all the mechanical properties and the variability of BFRC were significantly enhanced comparing with those of raw bamboo and other bamboo-based composites.

1. Introduction

In the 21 century, research of science and technology has moved toward renewable raw materials and processes which are more environmentally friendly and sustainable [1]. The use of natural plant fibers as reinforcement in polymer composites for making engineering materials has generated much interest in recent years [2]. Bamboo as sustainable resource, abundantly available and biodegradable, is widely used in producing bamboo-based composites such as bamboo plywood, laminated bamboo lumber, bamboo scrimber, bamboo particle board and bamboo fiber reinforcing polymer composite, which were found to have extensive applications in furniture, flooring, building and civil engineering field, especially in China and India [3–7]. The market size for bamboo products grows to 92.5 billion RMB, equivalent to 14.8 billion US dollars per year in 2010 and enjoys a compound annual growth rate of nearly 30% [8]. Therefore, the bamboo industries become the highlight of forestry.

Natural bamboo itself is a unidirectional fiber reinforced composite consisting of long and parallel cellulose fibers (vascular bundles) embedded in a ligneous matrix (ground tissues) [9]. The bamboo fibers called 'natural glass fiber' have a specific strength of 610 MPa, while the ground tissues, which are honeycomb foams, have a much lower strength of 50 MPa [10]. Because the bamboo fiber is often brittle and covered with lignin comparing with other natural fibers, it is difficult to extract bamboo fibers which have superior mechanical properties; therefore, it is expected to adopt a devised process to extract the bamboo fibers for reinforcement of composite materials. However, only few reports discussed the practical fabrication process of bamboo fiber and its composites, though several papers have already been published on the studies of bamboo-based polymer composites. The fabrication processes comprise chemical decomposition, steam explosion, and mechanical separation [4]. And the reinforcement forms include bamboo strips, bamboo sliver, bamboo bundle and bamboo fibers [4,11–13]. The bamboo fibers separated by steam explosion or chemical decomposition are usually short fibers, which disrupt the orientation of the natural bamboo fiber; consequently, the basic performances of bamboo are damaged. Besides, these processes consume abundant energy or chemical reagents. The bamboo strip, bamboo sliver and bamboo bundle produced using the mechanical separation process retain the natural characteristics of bamboo fibers. However, the outer layer and the inner layer of the bamboo show large different physical and mechanical properties compared with the main part of the bamboo and are difficult to be glued. Therefore, when bamboo strip, bamboo sliver and bamboo bundle are used to manufacture bamboo-based composites, the inner layer and outer layer of the bamboo must be removed in the process of structural units so as to meet the physical and mechanical properties of bamboo panels [8,9]. This inevitably reduces the efficiency and utilization of bamboo. Additionally, the resin is generally distributed in the surface of the units of bamboo strip, bamboo sliver or bamboo bundle, which makes it difficult to improve

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the properties of honeycomb foams. It is necessary to produce a novel unit using mechanical treatment without any chemical and moving the inner layer and outer layer of the bamboo. In previous work, a novel fluffer was developed for manufacturing the oriented bamboo bundle mat (OBFM).The fluffing rollers of the novel fluffer are composed of several special shaped gears with intervals between the teeth to make linear shaped cracks and the driving rollers arrange uniform convex pocks to generate dotted shaped cracks on the bamboo [8].

The objectives of this study are to produce bamboo fiber reinforced composite (BFRC) using oriented bamboo fiber mat (OBFM) and to investigate the mechanical properties of BFRC comparing with those of commercial bamboo scrimber (BS) and laminated bamboo lumber (LBL).

2. Materials and methods

2.1. Materials

Maso bamboo (*Phyllostachys pubescens*), age 3–4 years, was taken from Jian'ou Forest Reserve, Fujian province, east south of China. The matrix material used in this study was based on a commercially available low molecular weight phenol formaldehyde resin, supplied by Beijing Dynea chemical industry Co., Ltd, The trade name is PF162510 with the parameters as following: 45.59% of solid content, 36 CP·s of viscosity, 10–11pH, and ability of dissolve in water is 7–8 times. Bamboo scrimber (BS) and laminated bamboo lumber (LBL) used as reference samples were supplied by Fujian Huangcheng bamboo co., Ltd.

2.2. Preparation of oriented bamboo fiber mat (OBFM)

The bamboo was sawn into a bamboo tube with the length of 2600 mm, and then was split longitudinally into two semicircular bamboo tubes. Thereafter, the inner nodes were removed, and the semicircular bamboo tube was pushed into the fluffer along the grain direction. The bamboo tubes were fluffed along the longitudinal fiber direction to form a series of dotted and/or linear shaped cracks along the fiber direction; consequently, the netty structural OBFM was formed by the interlaced bamboo bundles fiber consisting of less than 5 vascular bundles and several ground tissues (see Fig. 1). The OBFMs were dried in the oven to an approximate moisture content of 10%.

Fig. 1. Picture of oriented bamboo fiber mat (OBFM).

2.3. Characterization of oriented bamboo fiber mat (OBFM)

2.3.1. Yield of OBFM

The yield of OBFM was calculated by the different weights between the raw bamboo and OBFM using the following equation:

$$\Delta m = \frac{m_1}{m_0} \times 100\%$$

where Δm is the yield of OBFM, m_1 and m_0 are the mass of the specimens before (the raw bamboo) and after (OBFM) mechanical treatment.

2.3.2. Morphology of dotted and linear shaped cracks

The dotted and linear shaped cracks of OBFM were observed with optical microscope (VHX-1000E), a new ultra-depth 3-dimensional microscopy system (UDM), made by KEYENCE.

2.4. Preparation of bamboo fiber reinforced composite (BFRC)

The solid content of phenolic-formaldehyde resin was adjusted to 15%. To obtain a uniform glue spread, the oriented bamboo fiber mats (OBFM) were immersed in the above resin for 6 min in room temperature. Thereafter, the OBFMs were taken out and placed vertically for 6 min until the adhesive on the surface stopped dropping. The amount of spread glue was controlled to about 13% of the oven dry weight of the OBFM during dipping glue process. Then the glued OBFMs were dried in 40 °C oven to a moisture content of 12%. The OBFMs were weighed out according to the desired density and were assembled along the grain direction with the outer layer outward and the inner surface inward so as to form the slab. The cold-in and cold-out technology was used in the hot-pressing process. The slab was sent into the press, when the temperature of the hot platen was around 60 °C. Next, the pressure and the temperature were increased due to the introduced superheated vapor to the press. The pressure was kept 3.5 MPa and the temperature was kept at 160 °C for a holding time of 0.5 min/mm. Then, the cold water was introduced into the press to eliminate the temperature to 60 °C, and then the pressure was released. Finally, the slab was taken out from the press and the needed assembly product of several bamboo fiber reinforced composites was obtained. The nominal dimensions of the BFRC were 2600 mm × 1300 mm × 25 mm in length, width, and thickness, respectively. Five replicated samples were prepared, tested and analyzed. All specimens were conditioned in a controlled environment room at 20°C and 65% relative humidity (RH) for 2 weeks before testing.

2.5. Mechanical properties of BFRC

The BFRC specimens were tested for their mechanical properties, such as modulus of elasticity (MOE), modulus of rupture (MOR),tensile strength (TS), compressive strength (CS), and short-Beam Strength (SS), according to the standard ASTM D-1037, ASTM D3500, ASTM D3500 type A, ASTM D3501, and ASTM D2344, respectively.

2.6. Micro-morphology analysis

The OBFM specimens were examined by scanning electron microscope (JEDL JSM-5500LV), and the surfaces of the BFRC specimens were examined by a stereomicroscopy (OLYMPUS SZX9) and SEM.