PLANT AGE EFFECT ON MECHANICAL PROPERTIES OF MOSO BAMBOO (*PHYLLOSTACHYS HETEROCYCLA* VAR. *PUBESCENS*) SINGLE FIBERS

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Abstract. Bamboo fiber has greater mechanical strength than certain other natural fibers and could therefore be a candidate for production of fiber-reinforced composites. Single fibers were isolated from Moso bamboo samples taken from plants between 0.5 and 8.5 yr old. Mechanical properties of single fibers (tensile strength, modulus of elasticity (MOE), and other mechanical related properties such as the microfibril angle and fiber cross-sectional area) were studied. There was no significant variation with age in average MOE and fracture strain of the bamboo fibers. Results indicate that the thickening growth of cell walls in bamboo fibers near the outer surface of bamboo is almost complete by 0.5 yr. Therefore, fibers from 0.5 to 8.5 yr old plants may be used for making fiber-reinforced composites.

Keywords: Moso bamboo, single fibers, tensile strength, MOE.

INTRODUCTION

Plant fibers are cheap, readily available, and easy to process. They also have low density, high aspect ratio, and high strength/weight ratio. Therefore, they could be used as a replacement for artificial fibers in fiber-reinforced composites (Glasser et al 1999; Baley 2002; Lee et al 2007; Ramires et al 2010; Yu et al 2011a,b). Furthermore, plant fibers are renewable and biodegradable with a low environmental impact for their whole life cycle (Robson et al 1996).

Bamboo fiber has greater mechanical strength than certain other natural fibers, such as wood, jute, coir, and straw. Therefore, bamboo fibers have been proposed as reinforcements in plastics, cement and concrete, rubber, and even aluminum (Low and Che 2006). The possibility of bamboo-fiber-reinforced composites has attracted interest in the fiber mechanical properties (Takagi et al 2003; Yu et al 2007). However, there is only a

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limited amount of data on mechanical properties of bamboo single fibers. Typically, bamboo single fibers are smaller than other plant fibers with diameters less than 20 μm and lengths less than 2 mm. This means that it is more difficult to obtain mechanical properties of bamboo single fibers because of the practicalities of gripping the fiber in a controlled orientation. We have developed a novel fiber gripping system and combined it with a high-resolution commercial mechanical tester. This system provides for fast and consistent mechanical characterization of single bamboo fibers (Yu et al 2011a).

Generally speaking, mechanical properties of bamboo increase with age of the plant, reaching a peak value at 3-6 yr and then decreasing. Gross mechanical performance of bamboo is therefore strongly dependent on age (Low and Che 2006). In bamboo, fibers are the primary load-carrying members. Thus, it is reasonable to assume that age of the plant may affect mechanical properties of bamboo fibers. In this study, effect of plant age on mechanical properties of bamboo single fibers was investigated to better understand the nature of the fibers and thus how best to select and use them. This information will be useful in the manufacture and optimization of fiber-reinforced composites.

MATERIALS AND METHODS

Sample Preparation

Samples of Moso bamboo (*Phyllostachys heterocycla* var. *pubescens*) from Huanggongwang Forest Park, Fuyang, Zhejiang Province, China, were selected and felled. The selected plants were known to be 0.5, 1.5, 2.5, 4.5, 6.5, and 8.5 yr old. The selected bamboos were straight and greater than 15 m high (Table 1).

Table 1. Moso bamboo sample characteristics.

Age (yr)	Diameter at 2 m height (mm)	Distance between nodes at 2 m height (mm)	Thickness of culm wall at 2 m height (mm)
0.5	131	230	10.6
1.5	110	252	9.5
2.5	102	258	10.2
4.5	120	230	9.3
6.5	117	237	10.6
8.5	105	222	11.0

A nominal 50 mm long cylinder was cut from halfway between adjacent bamboo nodes at about 2 m height immediately after harvesting. A 10 mm wide × 50 mm long block was cut from the cylinder. A 1.5 mm thick radial slice was cut from the block 1 mm from the outer surface of the bamboo. The microfibril angle (MFA) of the slice was first measured with X-ray diffraction (full method described subsequently), and the slice was then cut into several strips and macerated in 4 parts 30% hydrogen peroxide, 5 parts glacial acetic acid, and 21 parts pure water at 60°C for 60 h. Afterward, the slivers were washed at least eight times with distilled water. Fiber slurries were prepared from the slivers by stirring them with a glass rod in a test tube, and then they were dispersed on glass slides with a pipette and left to dry.

Microfibril Angle Test

The 50 mm long × 1.5 mm wide tangential slice samples were used to determine MFA using an X'PertPRO X-ray diffractometer (Philips, Eindhoven, The Netherlands). The radiation source was CuKa ($\lambda = 0.154$ nm). The tube voltage was 40 kV, and the current was 40 mA. The X-ray beam size was 4 × 2 mm, and the scattering angle 2θ was 22.4°. The scan time of each sample was 3 min. Diffraction strength curves were analyzed and used to calculate MFA.

Single-Fiber Tensile Measurement

As mentioned previously, bamboo single fibers are small (typically 2 mm long and 15 μm in diameter). Therefore, it is difficult to grip a single fiber using commercially available tensile test apparatus. To solve this problem, a special fiber gripping system was designed and integrated into a low-load high-resolution mechanical tester (Microtester 5848; Instron, Norwood, MA), the details of which are reported elsewhere (Yu et al 2011a).

A dissecting microscope was used to position a batch of 30 single bamboo fibers across grooves cut in a polyethylene board. Resin droplets (nominally 200 μm diameter) were placed on the ends of the fibers. After treating all fibers on a board, the fiber samples were oven-dried at 60°C for about 30 h until the resin was fully cured. Samples were then conditioned under ambient condition (25°C and 15% RH) for 1 d before testing.

For tensile testing, a constant strain rate of 0.8 μm/s and a preliminary tension force of 10 mN were set. Force-displacement curves were recorded during testing. Tensile strength, modulus of elasticity (MOE), and failure strain were calculated based on fiber cross-sectional area. At least 25 bamboo fibers were tested for each bamboo age.

Cross-Sectional Area Measurement

The 0.5 and 6.5 yr old bamboo fibers had circular cross-sections and cell cavities (Fig 1). This fiber cross-section and cell cavity morphology were, however, somewhat irregular, and similar cross-sections and cell cavity morphologies occurred in bamboo fibers of other ages. Because the value of a single fiber cross-sectional area was critical to our observations, both fiber cross-sectional area and cavity area needed to be measured with repeatable precision.

Confocal scanning laser microscopy (CSLM) was used to get a fast, precise measurement of the cell wall area. Broken fibers were stained with a 0.001 g/L acridine orange dilution for 5 min, and then the stained fiber segments were mounted between a glass slide and cover slip. CSLM was used to measure fiber cross-sectional area. Figure 2 shows a three-dimensional CSLM photograph of a bamboo single fiber. Fiber cross-sectional area was calculated using CSLM imaging software (Groom et al 2002a,b).

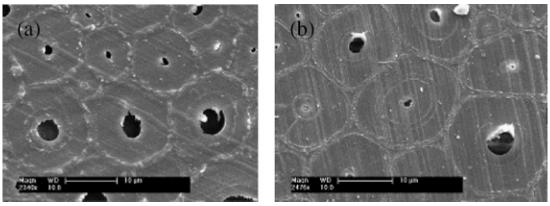

Figure 1. Bamboo cross-sections (a) 0.5 yr old (b) 6.5 yr old.

RESULTS AND DISCUSSION

Typical stress–strain curves from 0.5 yr old bamboo fibers are shown in Fig 3. No obvious yield and distinct slippage were seen during the whole tensile test. Similar stress–strain curves occurred in bamboo fibers of other ages. Also, it was found that more than 50% of the tested fibers broke at or near the central section.

Linearity was observed in the curves of all tested fibers (Fig 3). MFA is the dominant factor affecting shape of the stress–strain curve in softwood fibers (Groom et al 2002a). Stress–strain curves characteristic of fibers with an MFA less than 20° exhibit highly linear tensile test results.

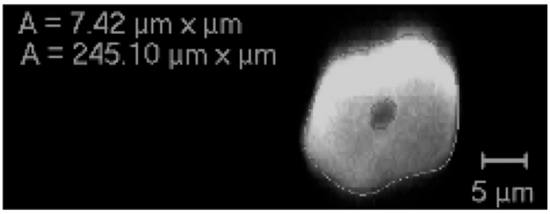

Figure 2. Cross-sectional areas of single bamboo fibers determined by confocal scanning laser microscopy.

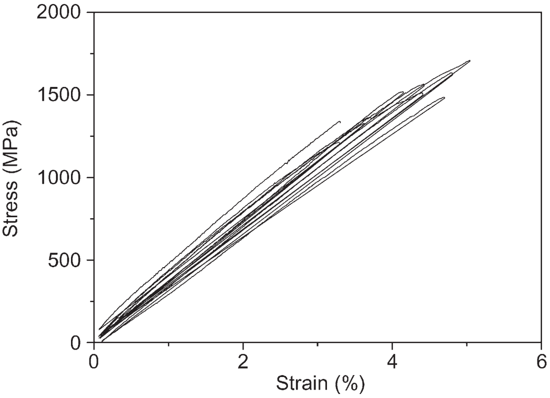

Figure 3. Stress–strain curves from 0.5 yr old bamboo fibers.

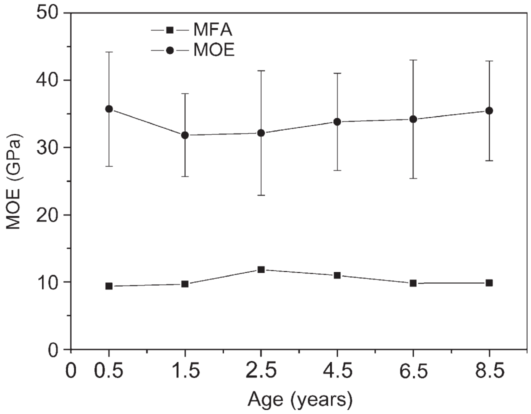

Figure 4. Variation of bamboo fiber modulus of elasticity with age (error bars represent standard deviation).

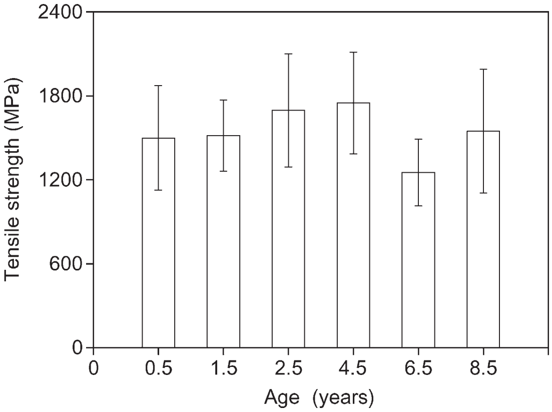

Figure 5. Variation of bamboo fiber tensile strength with age (error bars represent standard deviation).

Because the MFA of Moso bamboo fibers is less than 12° (Fig 4), linear stress–strain curves are to be expected from bamboo fibers.

For all tested bamboo fibers, average tensile strength and longitudinal MOE were 1.54 and 33.86 GPa, respectively, and average fracture force and fracture strain were 220.88 mN and 4.85%, respectively. Mechanical properties of bamboo fibers were higher than those of equivalent fundamental wood fibers reported by other researchers. Groom et al (2002a) found that MOE and ultimate tensile stress of loblolly pine latewood fibers ranged from 6.55-27.5 GPa and 0.41-1.42 GPa, respectively. Similar results were also obtained by Burgert et al (2002, 2005), who reported that ultimate tensile strength and MOE of Norway spruce were about 1.19 and 22.6 GPa, respectively. Compared with these wood fibers, our bamboo fiber had a smaller diameter (usually 10-20 μm) and the cell cavity was difficult to identify (Fig 1), indicating a thick cell wall. MFA of our bamboo fibers was small (ranging from 9.39° to 11.83°), which resulted in strong mechanical properties and flat bamboo fibers. The degree of flatness could have also indirectly affected mechanical properties of the bamboo fiber by decreasing shear failure. Finally, surface pitting on the fiber affects mechanical properties. The presence of pits is a possible weak point, and fractures often occurred in and near the pits. Therefore, size and number of pits have an important effect on mechanical properties of the fibers. Bamboo fibers had fewer pits than typical softwood fibers, and pit size was much smaller than those found in wood fibers. Our bamboo fiber had stronger and more stable mechanical properties than the wood fibers of previously mentioned literature.

Variations of fiber MOE and tensile strengths with age are shown in Figs 4 and 5. Magnitudes and distribution of MOE and tensile strengths of 0.5 yr old bamboo fibers were similar to those of other fibers, ranging from 23-53 GPa for MOE and 1-2.4 GPa for tensile strength. Thus, 0.5 yr old bamboo reached a plateau in mechanical properties, and subsequent variation of average mechanical properties with age was small. However, maximum tensile strength (2.77 GPa) and MOE (61.64 GPa) were all found in 4.5 or 6.5 yr old bamboo fibers. This was probably because of the higher density of these fibers caused by deposition of lignin in mature bamboo fibers.

Analysis of variance showed that there was no significant variation in MOE with age at the 0.05 level, whereas significant differences occurred in tensile strengths. We conclude that the MOE of bamboo fibers was not affected by age. It has been shown that MOE is highly dependent on MFA (Cave 1968, 1969; Page et al 1977). Our results showed that MFA was

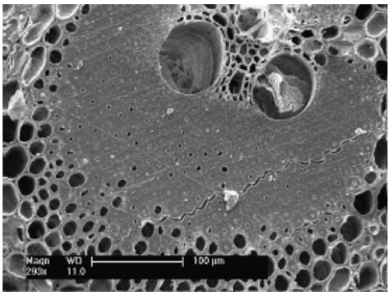

Figure 6. Vascular bundle in 0.5 yr old bamboo.

similar for all tested bamboo fibers (ranging from 9.39° to 11.83°) and was consistent with results reported elsewhere (Yu et al 2007). Because the major influencing factor (MFA) was similar (Fig 4), MOE should also be similar. Generally speaking, thickening growth of the cell wall for bamboo fibers was incomplete until the fourth or fifth year. Lybeer et al (2006) reported that there was no significant increase in cell wall thickness of the fiber in bamboo culms older than 1 yr. However, our fibers were taken near the outer surface of the bamboo, and Figs 1 and 6 show that 0.5 yr old fibers have a small cell cavity and thick cell wall. Average cross-sectional area of 0.5 yr old bamboo fibers (144.45 μm^2) was close to the mean cross-sectional area of the older fibers (147.84 μm^2). Our findings suggest that the cell wall thickening growth is almost complete in 0.5 yr old bamboo fibers near the outer surface; hence, for the outer bamboo fibers, further aging has no influence on MOE. Therefore, bamboo fibers of this age can be processed and used to replace other plant or manmade fibers in fiber-reinforced composites by the time they are 0.5 yr old. A shorter growing period effectively means that the raw materials are more abundant. Furthermore, the age of bamboo has little effect on processing or properties, therefore there is no need to separate for processing and use, which affords significant savings in cost and energy. For tensile strength, the observed differences could be artifacts of sample preparation and testing.

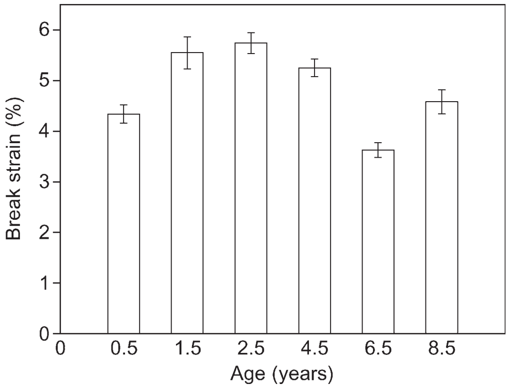

Figure 7. Variation in average breaking strain of bamboo fibers with age (error bars represent standard deviation).

Figure 7 shows that variations of mean fracture strain with age are typically distributed between 3.63 and 5.74%. The maximum of 5.74% was found in 2.5 yr old fibers, whereas the minimum (3.63%) was found in the 6.5 yr old fibers. There was no obvious variation or trend in fracture strain with age. However, it is difficult to conclude that our fracture strain results could be generalized because fracture of bamboo fibers was influenced by factors in the tensile test, such as the sample preparation having a weakening effect on the fiber and the nature of the measurement technique itself. The fracture strain of bamboo fiber was typically greater than that of wood fiber with a similar MFA (Burgert et al 2002). The greater toughness of the bamboo fiber compared with wood fiber may be because of the nature of the bamboo fiber cell wall structure. Bamboo fiber structure is characterized by a thick polylaminate secondary wall composed of alternating broad and narrow lamellae. We suggested that this particular structure results in the toughness of bamboo fibers.

CONCLUSIONS

Average tensile strength and longitudinal MOE of bamboo fibers were 1.54 and 33.86 GPa, respectively. Average fracture force and fracture strain were about 220.88 mN and 4.85%, respectively. Average values of fracture strain were between 3.63 and 5.74%. There were no significant variations in MOE with age at the 0.05 level, whereas significant differences occurred in tensile strength. Our results suggest that the thickening growth of the cell walls near the outer layer is virtually complete by 0.5 yr. Bamboo fibers between 0.5 and 8.5 yr of age satisfy the requirements for use in fiber-reinforced composites.

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