TENSILE PROPERTIES OF SINGLE RATTAN FIBERS

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(Received February 2014)

Abstract. The longitudinal tensile strength of single fibers of four rattan species, namely *C. simplicifolius*, *C. nambariensis* Becc. var. *yingjiangensis*, *C. nambariensis* var. *xishuangbannaensis*, and *C. yunnanensis*, was studied using a custom-built short vegetable fiber mechanical tester. The stress–strain curves produced by the four different rattans showed two distinct phases: a steep, straight segment in the initial phase followed by a straight line with a lower slope up to the breaking point. The respective average values for tensile elastic modulus, tensile strength, and elongation at breaking point of *C. simplicifolius, C. nambariensis*.var. *xishuangbannaensis, C. yunnanensis*, and *C. nambariensis* var. *yingjiangensis* canes were 10.61, 10.05, 9.10, and 9.54 GPa; 603, 566, 464, and 539 MPa; and 17.00, 17.24, 16.44, and 21.08%. The length position of the single fibers in the cane had variable effects on the three aforementioned properties for all four sampled rattan species. The tensile properties of *C. simplicifolius* fibers were highest. Compared with wood and bamboo, modulus of elasticity and tensile strength of the studied rattans were much lower, whereas elongation at breaking point of single rattan fibers was generally higher.

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Wood and Fiber Science, 46(4), 2014, pp. 519-526

Keywords: Rattan, tensile properties, single fiber, tensile elastic modulus, tensile strength, elongation at breaking point.

INTRODUCTION

Plant fibers are renewable, readily available, biodegradable, and combustible with minimal environmental impact during their whole life cycle (Robson et al 1993). Plant fibers possess versatile advantages of high strength-to-weight ratio and low density, which makes them a potential replacement for manmade fiber in fiber-reinforced composites (Baley 2002; Li et al 2009; Reddy and Yang 2009; Ramires et al 2010). Single fibers are the principal load-carrying component of fibrous materials and give excellent mechanical properties in fiber products. The study of mechanical behavior of single plant fibers is now gaining considerable interest not only because they can be used as reinforcement in fiber-based composite materials, but also because direct correlations can be made between mechanical fiber properties and the microstructure and chemical composition of plant cell walls. In this field, tensile testing of single fibers is a tool used to analyze mechanical properties at the cellular level. For example, pulped fibers from wood have been examined for their mechanical behavior as a function of tree species (Jayne 1959, 1960), microfibril angle (Page and El-Hosseiny 1983; Sedighi-Gilani Navi 2004), moisture content (Spiegelberg 1966; Ehrnrooth and Kolseth 1984), and hemicellulose content (Spiegelberg 1966). In addition to pulped wood fibers, some researchers have also studied the tensile strength of single wood fibers (Kersavage 1973; Burgert 2005; Marjan 2006; Keunecke et al 2008). Among these researchers, Groom et al (2002a, 2002b) and Mott et al (2002) have presented a systematic investigation of a loblolly pine tree showing the influence that the position of a fiber within a tree, both in terms of height and growth ring number, plays on the properties of individual fibers.

In recent years, the tensile properties of short, single bamboo fibers have also been investigated (Huang et al 2009; Cao et al 2010; Yu et al 2011a, 2011b; Nahar and Hasan 2013). For example, Yu et al (2011a) studied the tensile properties of single *moso* bamboo (*Phyllostachys pubescens*) fibers and analyzed the effect of moisture content on the tensile performance using a custom-built mechanical tester for fibers down to about 2 mm long.

Rattans are a renewable resource and are spiny, climbing representatives of the palm family in the Old World tropics. With their strength and flexibility, canes are easily bent and have multiple uses in weaving, matting, and fine basketry. Rattan, being a monocot, lacks the necessary lateral meristems to undergo secondary growth. Only limited diameter growth is possible through ground parenchyma cell enlargement (Tomlinson 1961). Rattan fibers, along with wood and bamboo fibers, are an interesting alternative to synthetic fibers. However, there is only limited information available on the tensile properties of single rattan fibers. To our knowledge, there is only one report on tensile properties of single rattan fibers for *Daemonorops margaritae* (Wang et al 2012).

To obtain a better and more comprehensive understanding of the mechanical behavior of single rattan fibers, four typical species of rattan, belonging to the genus *Calamus*, grown in the two major rattan distribution areas in China, were selected for testing. In this study, the mechanical properties of single fibers from four rattan species were investigated with the ball-and-socket system and a microtester for longitudinal mechanical properties determination of short vegetable fibers. Also, the variations of tensile properties were analyzed in the four rattans along the length of the cane.

EXPERIMENTAL

Materials

Canes of *Calamus simplicifolius* Wei. (A) were collected from Qiongzhong City, Hainan Province, China, whereas *C. nambariensis* Becc. var.

xishuangbannaensis S.J. Pei et S.Y. Chen (B), *C. yunnanensis* S.J. Pei et S.Y. Chen (C), and *C. nambariensis* Becc. var. *yingjiangensis* S.J. Pei et S.Y. Chen (D) canes were collected from Mengsong Village, Xishuangbanna City, Yunnan Province, China. To easily record observation, the four rattans were marked A, B, C, and D, respectively. Because the samples were selected from native stands, the ages of the four tested rattan samples were undefined. The average cane length and diameter of A, B, C, and D were 24.20 m and 17.6 mm, 13.14 m and 14.90 mm, 16.29 m and 12.7 mm, and 17.79 m and 23.2 mm, respectively.

Microtensile Test

Sample preparation. Three canes of each rattan species with mature appearance and without obvious signs of defects were selected. The selected canes were divided into several segments from base to top. Every segment contained 10 internodes. At the middle of each segment, a 30-mm height cylinder was sawn, and small cubic blocks with dimensions of approximately 1 × 1 × 5 mm (radial × tangential × longitudinal [R × T × L]) were cut from the cortex, middle, and core of each cylinder. Subsequently, the small cubic blocks were macerated in a mixture of glacial acetic acid and hydrogen peroxide (Groom et al 2002b) at 60°C for 14-16 h until the samples became white in appearance. Fibers were transferred to a glass slide using a pipette. Under a microscope, rattan fibers with minimal damage were carefully selected and placed across a gap on an organic glass panel. With super fine tweezers, two epoxy droplets with approximate diameters of 200 μm were then placed at the ends of each fiber with an approximate spacing of 0.7-0.8 mm. The epoxy was then allowed to solidify at 60°C for more than 8 h followed by an additional balance in room conditions for 24 h. Figure 1 shows a prepared sample of a single rattan fiber.

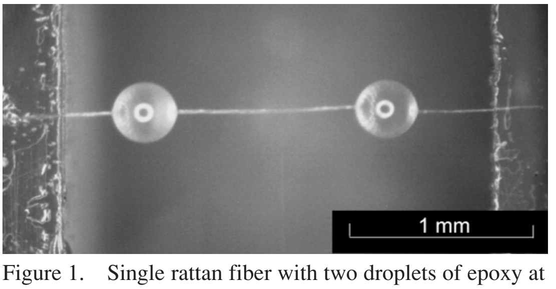

Figure 1. Single rattan fiber with two droplets of epoxy at its ends acting as anchoring points.

Microtensile test. In this study, a custom-built fiber gripping system was applied and combined to a small commercial high-resolution mechanical tester (Instron Microtester 5848, Norwood, MA). The load cell capacity was 5 N. Elongation was recorded from the crosshead movement with a displacement resolution of 0.02 μm and a constant rate of 48. The cell wall areas of every broken fiber were determined with a confocal scanning laser microscope (Meta 510 CSLM, Carl Zeiss, Jena, Germany). Details on the microtensile assembly, the longitudinal tension experiment procedure as well as the cross-sectional area measurements are referred to in Yu et al (2011a). For each section of the four rattan species, 30 fibers were tested.

Microfibril Angle Measurement

Three sections with dimensions of 1 × 10 × 20 mm (R × T × L) were cut from every 10th internode from base to top. Microfibril angle (MFA) was tested by a powder X-ray diffractometer (X'Pertpro, Panalytical, The Netherlands). The mean MFA of several hundred cells was determined by a diffraction pattern (Fig 2) according to the Gaussian fitting method of Cave (1997) and calculated by Eqs 1 and 2 with the method of 0.6 T. Two of Gaussian doublet fittings were adopted to decrease error.

$$y = a + b_1 \cdot \exp\left[\frac{-(x-u)^2}{2\sigma_1^2}\right] + b_2 \cdot \exp\left[\frac{-(x-u-180)^2}{2\sigma_2^2}\right] \quad (1)$$

where a is a constant; u and $u - 180$ are the center of two peaks; σ_1 and σ_2 are determined

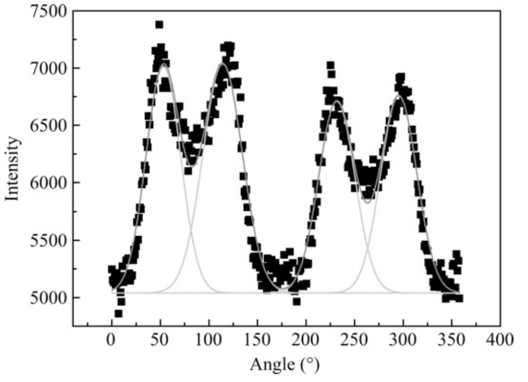

Figure 2. X-ray diffraction pattern of microfibril angle in rattan and Gaussian fitting.

by peak width at half height; and the following b_1 and b_2 mean peak height.

$$MFA = \frac{(T_1 + T_2 + T_3 + T_4)}{4} \times 0.6 \quad (2)$$

where $T_i = \sigma_1 + \sigma_2$ (i = 1, 2, 3, 4).

RESULTS AND DISCUSSION

Mechanical Behavior in Tension

Figure 3 shows the typical stress–strain curves of single rattan fibers under longitudinal tension. For all four rattans, although they have different slopes, the observed stress–strain curves show similar trends and exhibit plastic fracture. The curves for the four rattans can be divided into two phases: a straight segment in the initial phase followed by a slightly lower slope until the breaking point. This behavior is commonly found in plant tissues with large MFA in the S_2 layer (Navi et al 1995; Kohler and Spatz 2002; Keckes et al 2003; Keunecke et al 2008). In this study, the average MFA of all four rattans was greater than 23° (Fig 4). Yu et al (2011a) found that bamboo fibers with MFA of 10° exhibited linear stress–strain behavior to failure. The stress–strain curve and tensile behavior

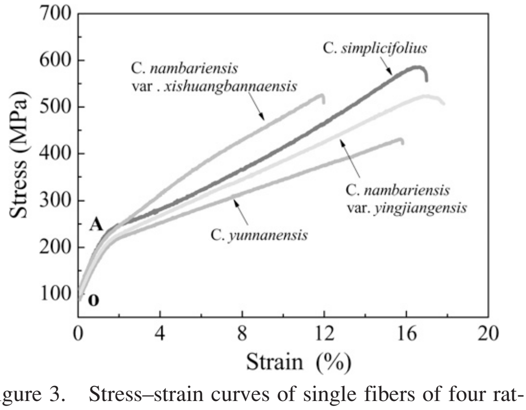

Figure 3. Stress–strain curves of single fibers of four rattan species under longitudinal tension.

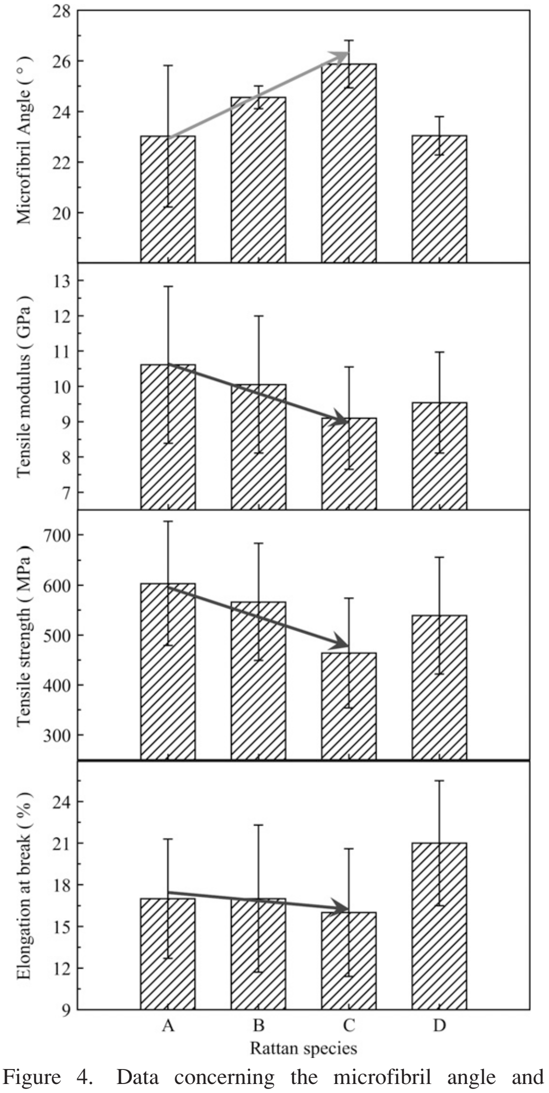

Figure 4. Data concerning the microfibril angle and mechanical properties of single rattan fibers.

of rattan are greatly different from that of single bamboo fibers (Huang et al 2009; Yu et al 2011a) that might be concerned with the large MFA of rattan.

Average and standard deviation values of tensile strength, tensile elastic modulus, and elongation at breaking point are presented in Fig 4. Analysis of variance (ANOVA) showed that the tensile elastic modulus, tensile strength, and elongation significantly differed in A, B, C, and D. The average values of tensile elastic modulus and tensile strength of A and C are 10.61 GPa and 603 MPa and 9.10 GPa and 464 MPa, respectively, representing the maximum and minimum values of the four rattan species sampled. This difference in mechanical performance could be affected by the MFA. The maximum value of elongation at breaking point was 21.08% in species D. For all four sampled rattan species, the average tensile strength and tensile elastic modulus were lower than that of *Phyllostachys pubescens* (Yu et al 2011a) and *Cunninghamia lanceolata* (Cao et al 2010), which produced values of 1560 MPa and 33.03 GPa and 1258 MPa and 19.90 GPa, respectively. This implies that rattan has weaker tensile properties than *moso* bamboo and *Cunninghamia lanceolata*. In contrast, the elongation at breaking point for all four rattans was higher than that observed in *Cunninghamia lanceolata* and Moso bamboo, which typically have average values of 6.6 and 7.0%, respectively (Cao et al 2010). This indicates that rattan is tougher than wood and bamboo, which is consistent with the stress–strain curve resulting from the four sampled rattan species. This is one of the reasons why rattan is such a good material for weaving applications.

Variation in Tensile Elastic Modulus Along the Length of the Cane

Figure 5 shows the variation in tensile elastic modulus of single rattan fibers in four rattan species along the length of the cane. ANOVA indicated that the tensile elastic modulus of A, B, C, and D significantly differed among all their internodes. The tensile elastic modulus of

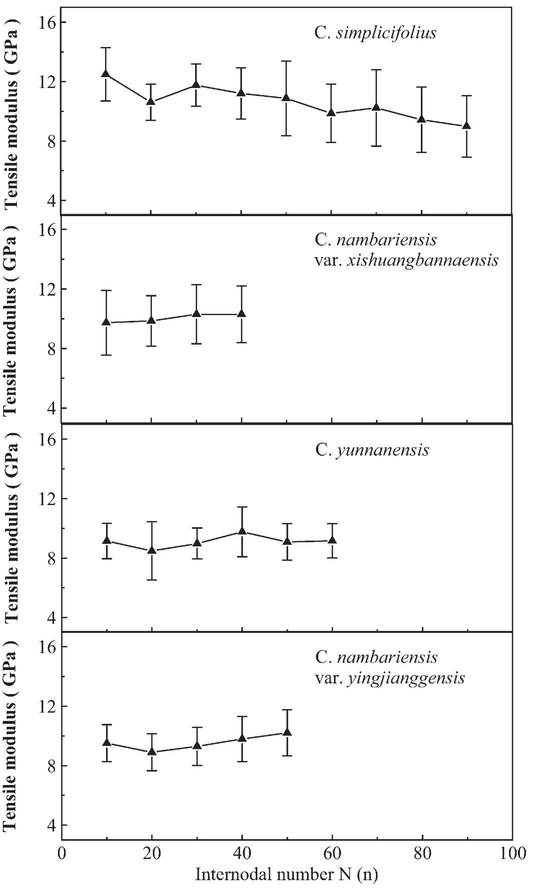

Figure 5. Variation in tensile elastic modulus of single fibers of four rattan species along the length of canes. Nodes are numbered from the cane base to the apex.

A samples exhibited a tendency to decrease as the cane length increased from the base to the apex. The greatest value of tensile elastic modulus for A was found at the 10th internode from the base to the apex, whereas the lowest value was observed at the 90th internode. Similar opinions were drawn by Chowdhury (2004) in evaluating macroscopic modulus of elasticity of *Daemonorops jenkinsiana* rattan cane. In contrast, although the degrees of increase vary among species, the tensile elastic modulus for B, C, and D samples tended to increase as the length of the cane increased. The tensile elastic modulus of B showed a linear increase. The tensile elastic modulus for C samples displayed a fluctuating trend along the length of the cane with the maximum value recorded at the 40th internode.

Variation of Tensile Strength Along the Length of the Cane

Variations in tensile strength along the length of the cane for single rattan fibers are shown in Fig 6. The variation in tensile strength of A, B, and C samples displayed a decreasing pattern with increasing length along the cane. Conversely, the tensile strength of D samples tended to increase as the cane length increased. ANOVA indicated that the tensile strength of A, B, C, and D significantly differed among all their internodes. The maximum tensile strength values for A, B, and C samples occurred at the 10th internode. However, the corresponding maximum value for D was found at the 50th internode near the top of the cane. The average value for tensile strength in A, B, and C samples decreased by 37.5, 10, and 36.7%, respectively, from the base to the top of the cane, whereas for D, the corresponding average value increased by 13.2% in the same direction.

Variation of Elongation at Breaking Point Along the Length of the Cane

Figure 7 shows the variation in elongation at breaking point for single rattan fibers from four

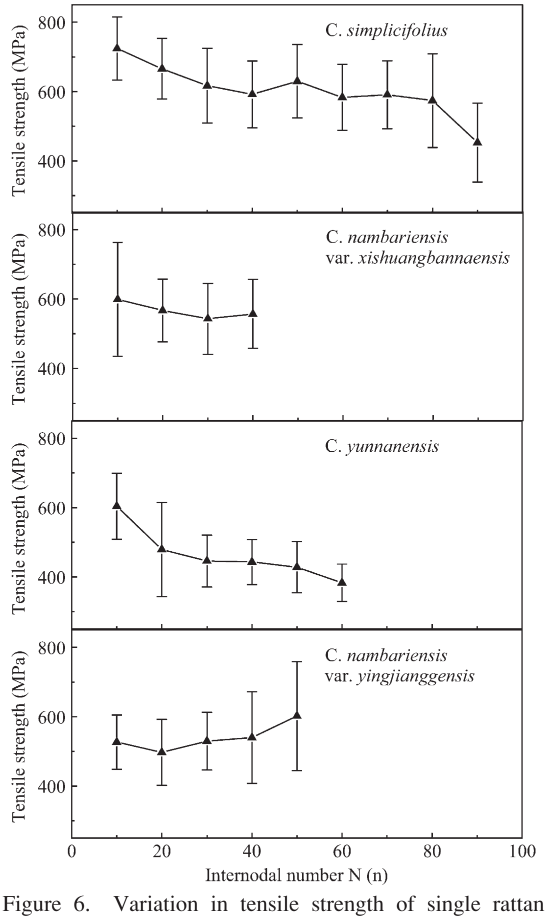

Figure 6. Variation in tensile strength of single rattan fibers of four rattan species along the length of the cane.

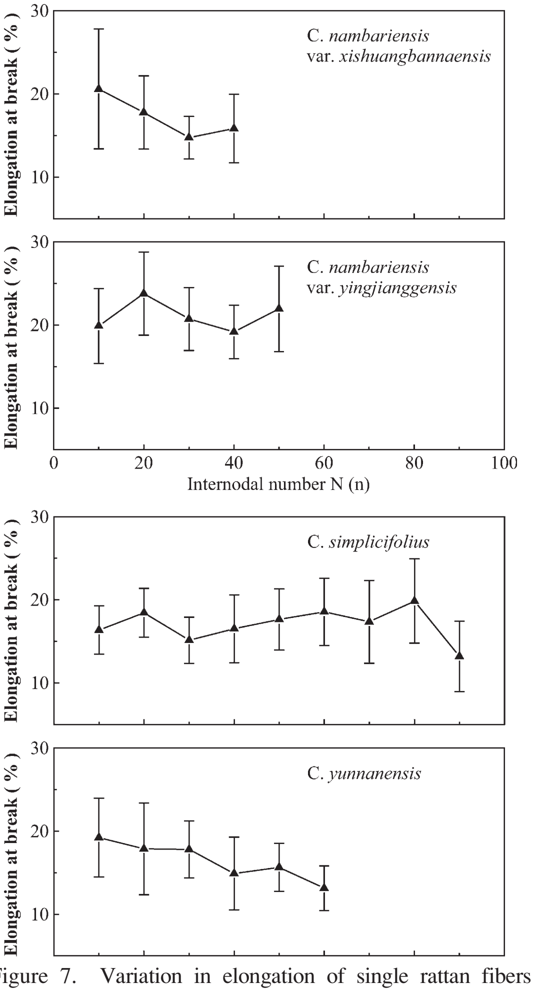

Figure 7. Variation in elongation of single rattan fibers from four different rattan species along the length of the cane.

different rattan species along the length of the cane. ANOVA indicated that elongation of A, B, C, and D significantly differed among all their internodes. For A and D samples, elongation at breaking point values fluctuated along the length of the cane with an obvious increase in elongation for A from the 30th to the 80th internode. The variation in elongation for B and C samples conversely shows a decreasing trend as the length of the cane increased. The maximum values of elongation for B and C are both recorded near the base position. Therefore, the relationship between length along the cane and elongation was the direct opposite of that for the tensile elastic modulus. This is consistent with the relationship between stiffness and toughness with the tensile elastic modulus representing stiffness and the elongation representing toughness.

From this study, *C. simplicifolius* canes were judged to have better tensile properties, whereas *C. nambariensis* var. *yingjiangensis* canes had better toughness properties. This may have been caused by the different MFA and species. Bhat (1992) thought that species, age, stem position, specific gravity, and moisture content were the important factors influencing mechanical behavior of canes. Mohmod and Yahaya (1992) considered that vascular bundle frequency and fiber wall thickness were correlated with mechanical properties. Abasolo et al (2000) found that a nonlinear relationship existed between MFA and the longitudinal Young's modulus. Therefore, the mechanical properties of rattan are determined by its complex structure and chemical composition. In the future, more work should be done to determine the correlation between mechanical properties of single rattan fibers and all the previously mentioned attributes.

CONCLUSION

The mechanical tension properties of single fibers of four rattan species were tested and compared. The stress–strain curves showed similar trends and consisted of two phases: a steep segment in the initial phase followed by a less steep phase. The MFA of four rattan canes were all beyond 23°. The four species of single rattan fibers had lower tensile elastic modulus and tensile strength and higher elongation at breaking point than bamboo. Among the tested samples, *C. simplicifolius* fibers with smaller MFA were found to have better tensile properties. The mechanical properties significantly differed among the internodes. However, the length position of the single fibers in the sampled canes had variable effects on the tensile elastic modulus, tensile strength, and elongation at breaking point.

ACKNOWLEDGMENTS

We thank the Chinese National 12th Five-Year Plan Science and Technology Project (2012BAD54G01) for providing financial support for this research.

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