TENSILE PROPERTIES OF FOUR TYPES OF INDIVIDUAL CELLULOSIC FIBERS

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Abstract. This research is intended to expand information on fiber characteristics for better understanding their complexity and potential in industrial use. Tensile properties of four types of individual cellulosic fibers, bamboo, kenaf, Chinese fir, and ramie, were measured by a custom-designed microtensile tester. Load-displacement curves for most individual fibers were found to be linear until failure. Average values of at least 30 individual fibers of bamboo, kenaf, Chinese fir, and ramie were 1685, 983, 908, and 1001 MPa for tensile strength; 26, 19, 14, and 11 GPa for tensile modulus; and 7.1, 5.4, 8.3, and 8.9% for elongation at break, respectively. Cross-sectional areas of cell walls measured by confocal laser scanning microscopy were 117, 140, 217, and 337 μm^2, respectively, an inverse relation with tensile modulus. Among the fibers, bamboo had the greatest tensile strength and modulus, whereas the other three did not have any statistical difference. Ramie had the largest elongation at break and the lowest modulus. Elongation at break of kenaf was significantly smaller than that of the other fibers. Fracture morphologies and load-displacement curves indicated these fibers were brittle materials. Tensile data can be used to screen fiber applications.

Keywords: Kenaf, bamboo, ramie, softwood, cellulosic fibers, microtensile, mechanical properties.

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INTRODUCTION

Natural fibers include bast, such as kenaf and hemp, hard fibers from leaves, such as sisal, fibers from seed, such as cotton, and others. Wood fiber is the most abundant fiber in the world with an annual production of 1750×10^6 tons/yr, whereas cotton production is 18.5×10^6 tons/yr, kenaf 0.97×10^6 tons/yr, flax 0.83×10^6 tons/yr, and hemp 0.21×10^6 tons/yr (Eichhorn et al 2001). Recently, there has been increasing interest in using natural fibers to replace synthetic glass or carbon fibers to fabricate different fiber-reinforced polymer composites. Natural fibers are lightweight, low-cost, and environmentally friendly. In the 20th century, production of renewable bio-based products, such as clothing and textiles from natural fibers, steadily declined, mainly as a result of substitution with petroleum-based synthetic materials (van Wyk 2001). Facing challenges of national energy security, environmental protection, and domestic economic growth, research activities have been intensified recently worldwide in developing natural fiber-reinforced composites (John and Thomas 2008). Bamboo and softwood have been reliable fiber resources for centuries, whereas kenaf and ramie are emerging fibers. Historically, these plants have produced high-quality fibers for pulps and papers, cordage, and textiles. To capture more value from natural fiber resources, cellulosic fibers can be substituted for synthetic fibers as reinforcements in polymeric matrices, enabling production of economical and lightweight composites for structural applications.

Efficiency of fiber reinforcement in composite material is primarily dependent on mechanical properties of reinforcing fibers and their adhesion to matrices. Tensile properties of natural fibers have been widely investigated at different hierarchical levels. Most often, resultant composites are fabricated and coupons are characterized in the screening of fiber candidates (Adekunle et al 2010). Fiber bundles in bamboo, kenaf, and ramie plants are aggregates of 10-40 elementary individual fibers held together by so-called gums such as lignin and pectin. Tensile properties of fiber bundles were measured for kenaf (Xue et al 2009), ramie (Kim and Netravali 2010a), bamboo (Rao and Rao 2007), and other cellulosic fibers (Baley 2002; Defoirdt et al 2010) because of the ease of preparing fiber bundle samples and convenience of using a bench universal testing machine by attaching fiber bundles to paper frames. The best practice in testing fiber bundles in tension is ASTM D 3822 Standard for Tensile Properties of Single Fibers (Symington et al 2009). The cross-sectional area of a piece of fiber bundle was measured with a digital micrometer or stereomicroscope without considering lumens in the fiber bundle. In contrast to the shapes of synthetic or regenerated fibers, which are well controlled during manufacturing, irregularity and complexity of fiber bundle cross-sections were a source of uncertainty for measuring tensile properties (Munawar et al 2007).

Individual cellulosic fibers vary 2-5 mm in length and 10-50 μm in diameter. The microdimension presents substantial challenges to perform tensile tests on individual fibers. Despite this difficulty, tensile properties have been investigated at the individual fiber level for softwood with specific devised in-house microtensile testers (Wang et al 2011). Mechanical properties of pulped softwood fibers have been examined correlating individual fiber strength with paper strength (Page and El-Hosseiny 1983; Mott et al 1995; Tchepel et al 2006). Chemically macerated fibers of southern pine have been investigated to gain insight into micromechanical properties of wood components and variability within trees for a better understanding of mechanical behavior of wood and its complex design (Groom et al 2002; Mott et al 2002). Mechanically isolating fibers of Norway spruce have been intensively examined with an improved method (Burgert et al 2003; Eder et al 2009).

However, strength and modulus for other nonwood fibers at the individual cell level are rarely reported in the literature. In fiber reinforcement application, fiber bundles are usually

pulped into individual cells to facilitate uniform dispersion in matrix. For predicting strength performance of fiber-reinforced composites through a modeling or simulation method, individual fiber tests to obtain single fiber properties are essential. The objective of this research was to evaluate mechanical properties of four types of individual fibers, providing a database for screening fiber applications. A special microtensile tester has been devised (Wang et al 2011). A systematic study was conducted on individual fibers generated from kenaf bast, wood, bamboo, and ramie, enabling a comparison of different species under similar conditions, using consistent single fiber preparations, a custom-designed microtester, and a confocal laser scanning microscope.

EXPERIMENTAL

Materials

Kenaf used in this study was cultivated in the experimental field of the Mississippi Agriculture and Forestry Experiment Station. Kenaf basts were separated after soaking fresh stems in water for one night at room temperature. Prepared kenaf basts were then cut into 51-mm-long strands.

Wood blocks of latewood ($30 \times 10 \times 1$ mm^3) were cut in the longitudinal tangential direction from the 5th and 26th growth rings of a 30-yr-old Chinese fir harvested from a tree farm in China. Specimens were obtained from a tree height of 1.5 m. Blocks were then processed into small, thin sticks.

Transverse sections of culms of three ages (2, 4, and 6 yr old) were taken of meso bamboo in the middle part of bamboo culms obtained from Xiaoshan, Zhejiang, China. From the middle of the culm wall of these sections, small sticks containing vascular bundles were dissected using a sharp scalpel. Because the maturation process from the outside of the culm wall toward the inner side was apparently clear, fibers in the middle of the culm wall were investigated.

Kenaf and Ramie Fiber

Kenaf fibers were obtained from kenaf busts through a mild chemical retting process. Specifically, the 51-mm-long kenaf bast strands were immersed in 5% NaOH solution in a pressure reactor (Parr Instrument Co., Moline, IL; 2 L) for 1 h with mild agitation at a temperature of 110-160°C (Shi et al 2007). Fibers were then neutralized with dilute acetic acid, rinsed with water, and dried in a laboratory oven at 103°C overnight and then stored at 25°C and 40% RH at least 3 da before testing. Ramie fiber was collected from Hunan Huasheng Zhuzhou Cedar Ramie Co., Ltd. (Hunan, China) and cleaned with deionized water several times to eliminate any contaminations.

Chinese Fir and Moso Bamboo Maceration

Sticks of Chinese fir and bamboo were immersed in a solution of one part 30% hydrogen peroxide, four parts distilled water, and five parts glacial acetic acid and placed in an oven at 60°C for about 24 h. Samples were then taken out and washed until the smell of acid was gone. Individual fibers (tracheids in Chinese fir and sclerenchyma fibers in bamboo) were separated mechanically using fine tweezers and stored at 25°C and 40% RH at least 3 da before testing. Prepared individual fibers were examined with an environmental scanning electron microscope (ESEM), and surfaces were found to be smooth without residuals of pectin, lignin, and hemicelluloses (Fig 1).

Tensile Test

A custom-designed microtester (SF-I) was used to conduct tensile tests. Under a stereo microscope, fiber samples with minimal damage were carefully selected from chemically macerated fibers. The two ends of a fiber were taped on a Plexiglas plate across a 1.8-mm-wide slot, and two epoxy droplets 50 μm in diameter were placed near the ends of the fiber. Several samples were prepared on one glass slide. The Plexiglas plate carrying the individual fibers was

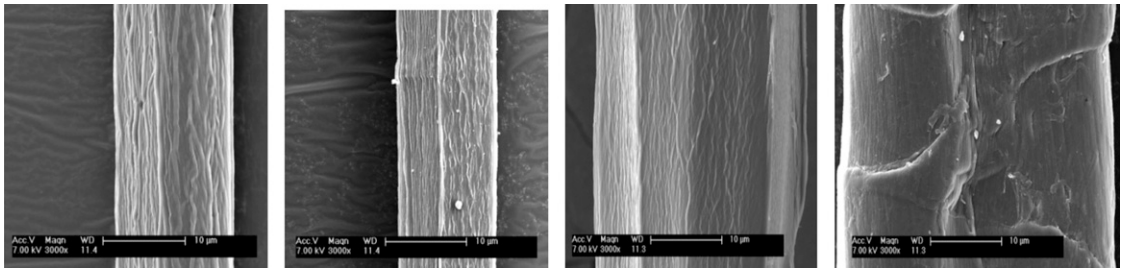

Figure 1. The typical environmental scanning electron microscope images of longitudinal section of an individual fiber (left to right: bamboo, kenaf, Chinese fir, ramie).

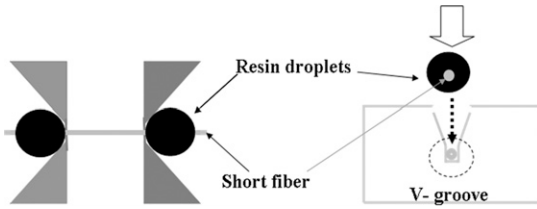

Figure 2. Ball and socket system of a single fiber.

dried at 60°C for 24 h and then equilibrated at 25°C and 40% RH overnight. The fibers with two cured epoxy droplets were then taken off the Plexiglas plate. Adhesive was not observed to penetrate or flow along the fiber cell wall after curing.

Fibers were carefully placed between two grips with the help of vertical and horizontal charge-coupled device (CCD) cameras inside the environmental chamber. Epoxy droplets on each end of the fiber were held in place creating a self-aligning ball and socket grip (Fig 2). An x-y-z adjustable stage was used to adjust separation length of the two grips to fit the length between epoxy droplets on the fiber and align the fiber to the tension direction. Tensile properties of individual fibers were tested using a 980.7-mN load cell with a resolution of 0.098 mN. Displacement was recorded from the crosshead movement with a resolution of 0.078 μm. Pretension of 10 mN was applied to the fiber. The distance between two droplets was determined as the gauge length with a vertical CCD camera. Nominal gauge length was about 0.7 mm, and the crosshead speed was 0.8 μm/s. Tensile properties were measured on 150 individual kenaf fibers, 60 Chinese fir fibers (mature and juvenile latewood, 30 each), 90 bamboo fibers (2, 4, and 6 yr old, 30 each), and 30 ramie fibers.

Cross-Sectional Area Measurement

Confocal laser scanning microscopy (CLSM; LSM 510 Meta; Zeiss, Oberkocken, Germany) was used to obtain images of cross-sections. CLSM has better lateral resolution than the conventional optical microscope, and it simplifies specimen preparation compared with electron microscopy (Jang et al 1992). Epoxy droplets of broken fibers were removed under a stereo microscope (SZ66; Beijing Fu Kai, Inc., Beijing, China) with a pair of microscissors. To enable fibers to fluoresce when subjected to an excitation laser source, broken fibers were stained in a 0.001% (w/v) acridine orange solution for 4 min at room temperature. Broken fiber segments were attached to a glass slide with tissue tack and allowed to air-dry. One droplet of balsam Canada reagent was placed on the slide, and a cover was carefully placed over the fiber, ensuring that no air was trapped. Images of cell cross-sections near the broken face of two broken segments were acquired with CLSM. Fiber cell wall areas were then measured with software provided by the instrument producer in a manner shown in Fig 3, ie cross-sectional cell wall area was equal to the difference between cross-sectional area and lumen area. The average of two areas near broken faces of two broken segments was used as the cell wall cross-sectional area of an individual fiber.

Load-displacement curves were then converted into stress–strain curves.

Microfibril Angle Measurement

An X-ray diffractometer (X'pert pro; Panalytical, Almelo, The Netherlands) was used to determine average microfibril angle (MFA) on the five samples before maceration. A point-focused X-ray beam was applied to the tangential section with a scanning angle range of 0-360° and a scanning step of 0.5°. From obtained intensity curves of X-ray diffraction, MFA of samples was determined. Groom et al (2002) reported that individual MFA can be measured for each fiber studied using CLSM. In that situation, the fracture mode of microfibril pullout from loblolly pine fibers under tension facilitated MFA measurement. However, brash failure modes of fibers from bamboo, ramie, and kenaf made it difficult to measure MFA of each fiber in a similar manner in this study.

Analysis of Variance

A multiple comparison with Fisher's least significance difference (LSD) method at $\alpha = 0.05$ was carried out to show differences among various variables with SAS software.

RESULTS AND DISCUSSION

Typical cross-sectional images by CLSM and ESEM are shown in Figs 3 and 4. Both kenaf and bamboo had a thick secondary cell wall with a very small lumen in polygonal shape, which indicates that both fibers underwent extensive cell wall thickening during maturation. Ramie individual fiber was flattened and typically hexagonal or oval in shape, whereas those of Chinese fir were rectangular in cross-section. ESEM images of cross-sections of these fibers were also in agreement with CLSM observations. Cell wall cross-sectional areas of individual fibers varied 59-245 μm^2 for bamboo, 63-351 μm^2 for kenaf, 139-411 μm^2 for Chinese fir, and 193-496 μm^2 for ramie. Average cell wall cross-sectional areas of bamboo, kenaf, Chinese fir, and ramie were 117, 140, 217, and 337 μm^2, respectively. Bamboo had the smallest mean cross-sectional area of fiber cell wall and standard deviation, whereas ramie fiber had the largest mean area and standard deviation (Table 1). Multiple comparison results from Fisher's LSD method indicated that there were statistical differences among the fiber types. However, distributions of cell wall areas of kenaf and bamboo apparently overlapped (Fig 5d). Variations in cell wall cross-sectional areas can be partially attributed to location of fibers in stems and the maturity state of fibers. Variations also may have been caused by uncertainty of sample preparations and testing.

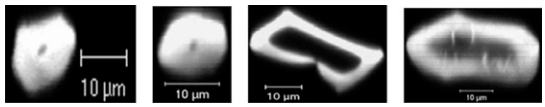

Figure 3. The typical confocal laser scanning microscopy images of cross-sections of individual fibers (left to right: Bamboo, Kenaf, Chinese fir, and Ramie).

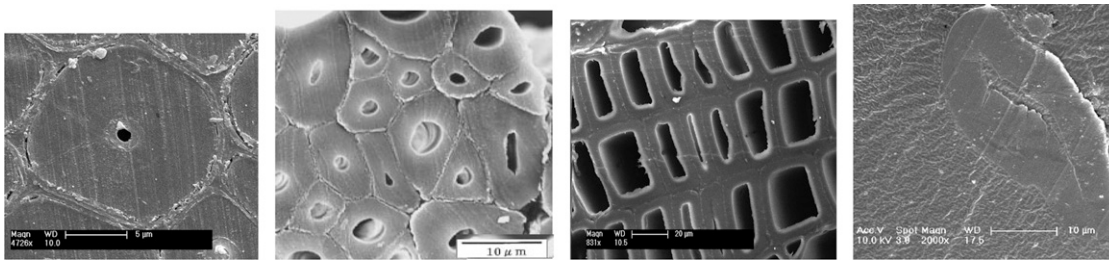

Figure 4. The typical environmental scanning electron microscope images of cross-sections of individual fibers (left to right: bamboo, kenaf, Chinese fir, ramie).

Table 1. Mean properties of ramie, fir, kenaf, and bamboo[a]

Mean/SD[b]/LSD	Tensile modulus (GPa)			Tensile strength (MPa)			Cell wall area (μm^2)			Elongation at break (%)		
Ramie	11	1.9	C	1001	153	B	337	78	A	8.9	1.6	A
Chinese fir	14	6.7	C	908	418	B	217	52	B	8.2	2.5	A
Kenaf	20	7.6	B	983	194	B	140	44	D	5.4	1.7	C
Bamboo	26	4.8	A	1685	293	A	117	35	C	7.0	1.1	B

[a] Means with the same letter are not significantly different at $\alpha = 0.05$.
[b] SD, standard deviation; LSD, least significant difference.

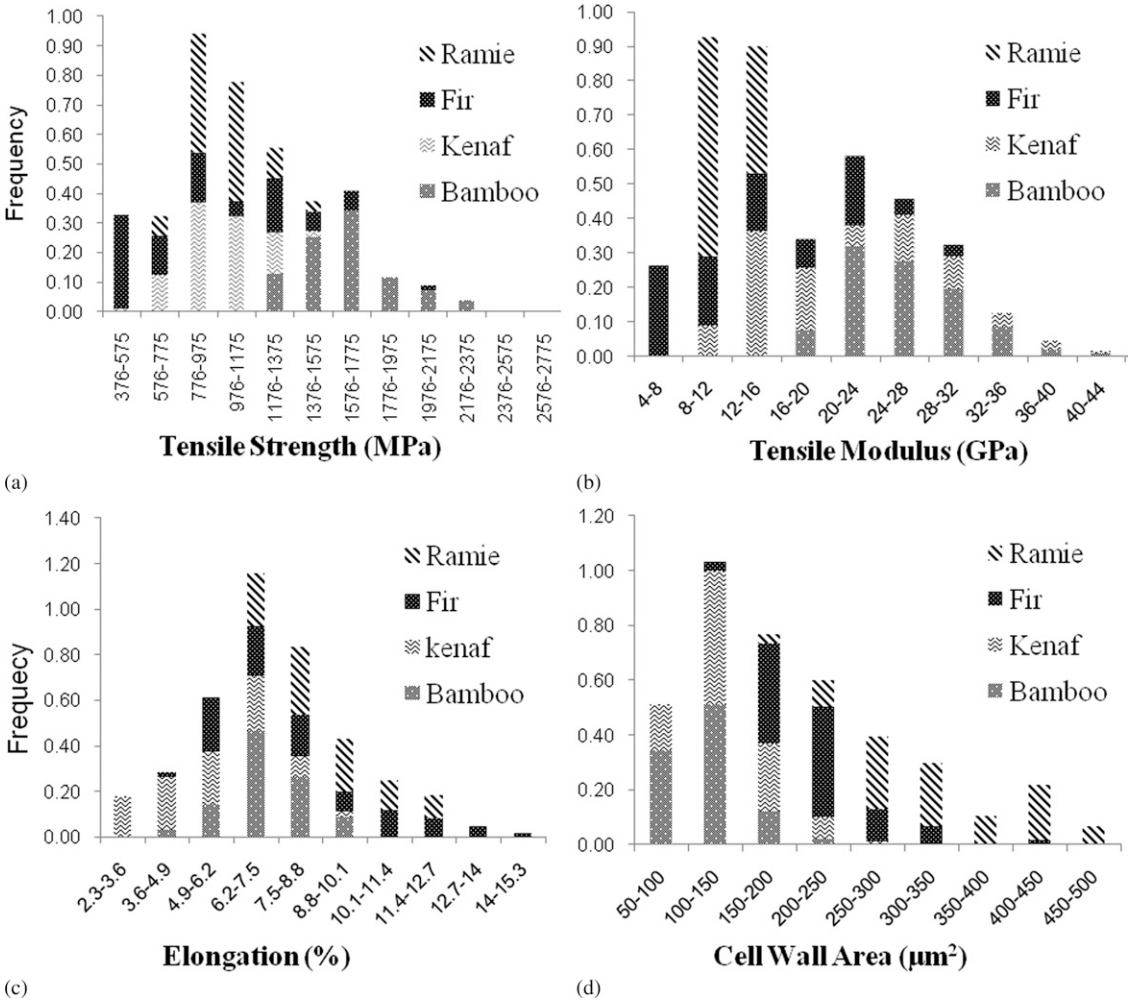

Figure 5. Comparison of property distributions of ramie (samples: 30), Chinese fir (60), kenaf (150), and bamboo (90). Y-axis is the fraction distribution and sum of the column of each fiber type is unity (100%).

Typical load-displacement curves (Fig 6a) and converted stress–strain curves using the cell wall cross-sectional area (Fig 6b) showed that fibers were linear and brittle in tensile properties except for Chinese fir juvenile latewood fiber, which demonstrated curvilinearity (Wang et al 2011). Global averages, standard deviations and distribution of tensile modulus, tensile strength,

elongation at break, and cross-sectional area of four fibers are summarized in Table 1 and Fig 5, which provide visual comparisons of means and distributions among various fibers. Bamboo individual fiber had the greatest tensile strength, 1685 MPa with a standard deviation of 293. The next greatest was ramie with 1001 (153) MPa, then kenaf with 983 (198) MPa, and last was fir with 908 (418) MPa. Tensile strength of bamboo was statistically higher than that of the other three fiber types. No significant difference in tensile strength was found among kenaf, fir, and ramie fibers. As shown in Fig 5a, strengths of kenaf, fir, and ramie center on a similar location with a larger spread for fir. Among wood species, tensile strength is proportional to MFA (Page and El-Hosseiny 1983; Burgert et al 2002). The greater MFA of Chinese fir fibers (Table 2) may account for their lowest tensile strength. However, kenaf and ramie have similar MFA to bamboo but with significantly lower tensile strength. This implies that MFA may not be a dominant factor in determining variation in tensile strength among different types of fibers. The high tensile strength in bamboo may be attributed to the combination of the multilayered structure of the fiber cell wall with alternating broad and narrow lamellae, low MFA, and scarcity of pits on the cell wall (Yu et al 2011).

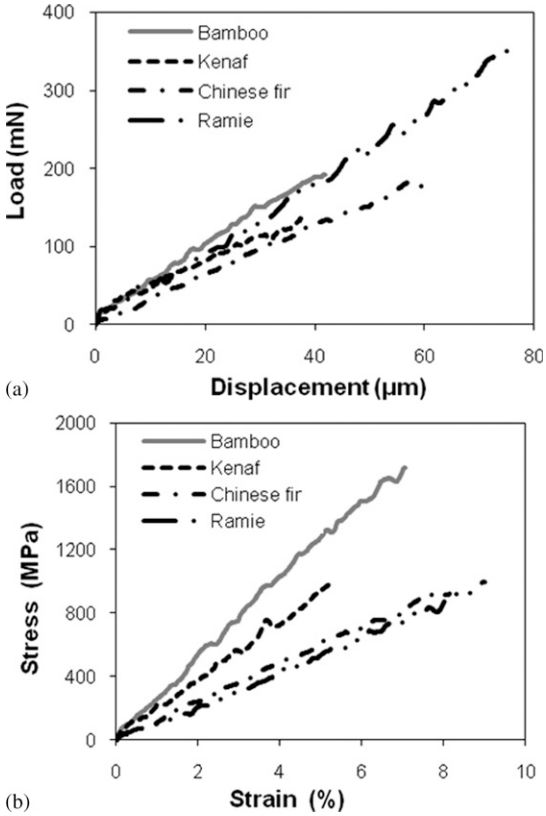

Figure 6. The typical load-displacement (a) and stress–strain (b) curves of the individual fibers.

Fiber tensile moduli (standard deviation) of bamboo, kenaf, Chinese fir, and ramie were 26 (4.8), 20 (7.6), 14 (6.7), and 11.4 (1.9) GPa, respectively. Bamboo had the highest tensile modulus, and kenaf bast ranked second, whereas moduli of ramie and fir were not significantly different by Fisher's LSD test. Tensile modulus was inversely proportional to cell wall cross-sectional areas. The flattened shape and larger lumens of Chinese fir and ramie fibers may account for their lower tensile modulus.

Average elongations at break for ramie, fir, bamboo, and kenaf were measured as 8.9, 8.3, 7.1, and 5.4%, respectively. Both ramie and Chinese fir fibers that had significantly larger elongation had more flattened cross-sections than those of kenaf and bamboo fibers showing polygonal shape. Kenaf had the smallest elongation at break.

Fracture modes of bamboo, kenaf, Chinese fir, and ramie fibers are shown in Fig 7. Fracture faces of most bamboo, Chinese fir, and ramie

Table 2. Measured MFA of bamboo, fir, and ramie

Types	Bamboo 2 yr	Bamboo 4 yr	Bamboo 6 yr	Mature wood	Juvenile wood	Kenaf	Ramie
MFA (degrees)	9.9	9.6	9.8	15.2	34.9	10[a]	10.2

[a] Reddy and Yang 2007.
MFA, microfibril angle.

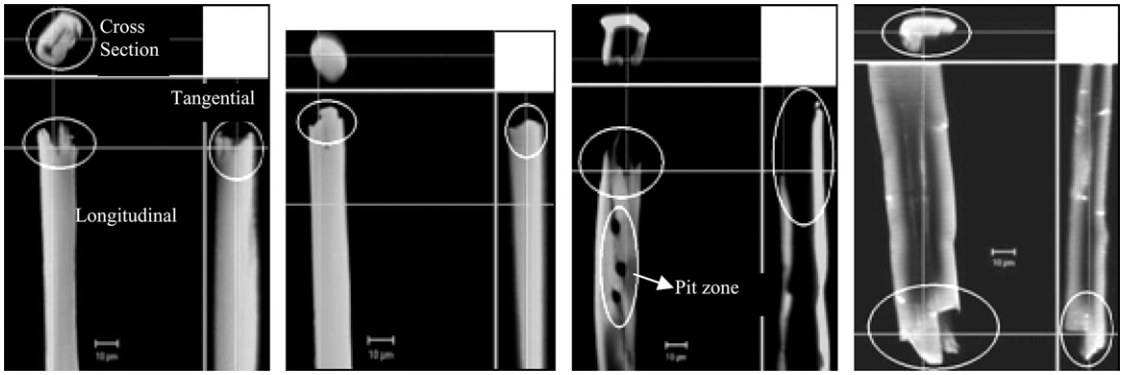

Figure 7. The typical confocal laser scanning microscopy images of the fracture morphology of an individual fiber (left to right: Moso-bamboo, kenaf, Chinese fir, and ramie).

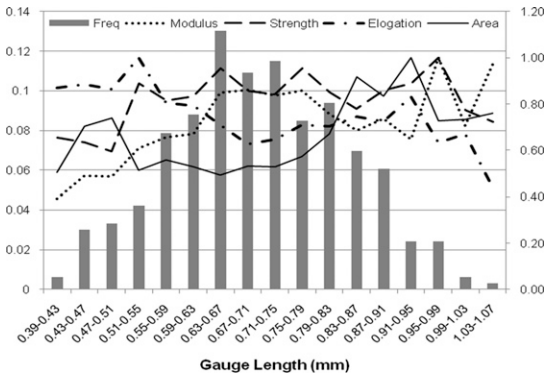

Figure 8. Histogram of all gauge length and its relationship with normalized properties.

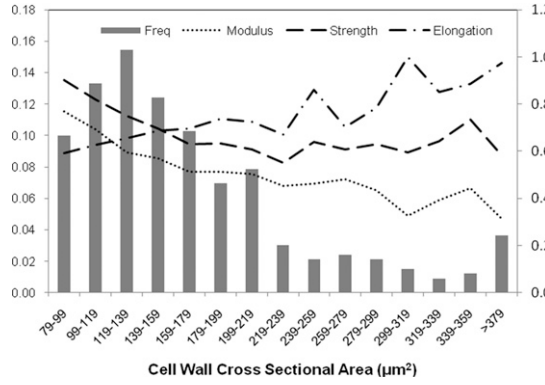

Figure 9. Histogram of all cell wall cross-sectional area and its relationship with normalized properties.

fibers were of oblique tooth profiles. The fibers generally broke in the pit-concentrated regions or where defects were located. Fracture surfaces of kenaf fibers were smoother than those of the other three fibers and were characterized by a typical brittle fracture appearance. This agreed with the smaller elongation of kenaf fiber.

Fiber strength depends on the "weak link" such as defects of dislocation, kink, and crack between gauge lengths. The longer the gauge length and/or the larger the fiber diameter, the higher the probability that the fiber contains defects and the lower the average fiber strength (Baley 2002). In this study, the nominal gauge length of 0.7 mm was controlled during sample preparations by a 1.8-mm slot on a glass slide and with two adhesive droplets near the ends of the fiber. Actual gauge length followed a normal distribution (Fig 8). Plots of strength, modulus, and elongation at break vs gauge length distribution did not obviously show that these mechanical properties were affected by gauge length distribution at this level. This observation implied that mechanical properties were controlled by intrinsic structures of the fiber rather than random distribution of defects between gauge lengths. This is different from those tests of longer fiber bundles with size effect (Baley 2002). However, plots of mechanical properties vs cell wall cross-sectional area showed that tensile modulus and strength of the fiber decrease as cell wall area increases (Fig 9).

Table 3. Properties of bamboo, Chinese fir, and ramie fibers[a]

Index	Treatment	Modulus (GPa)	LSD test	Strength (MPa)	LSD test	Elongation (%)	LSD test	Area (μm^2)	LSD test
Kenaf	Average	20	C	983	C	5.4	D	140	D
Moso bamboo	2 yr	24	B	1590	B	7.2	C	129	E
	4 yr	27	A	1710	A	7.0	C	113	E
	6 yr	26	A	1755	A	7.0	C	111	E
Fir latewood	Mature	20	C	1258	B	6.6	C	231	B
	Juvenile	9	E	558	D	9.9	A	203	C
Ramie		11	D	1001	C	8.9	B	337	A

[a] Means with the same letter are not significantly different at $\alpha = 0.05$, at least 30 samples.
LSD, least significant difference.

Therefore, the larger the cell wall cross-sectional area, the higher the probability that the fiber contains defects.

Average properties of all the fiber types are summarized in Table 3. Comparisons among subgroups of each fiber type might not be meaningful because fibers were not prepared the same way. The comparisons within groups were examined to disclose effects of treatment, age, or location on fiber properties. As shown in Table 3, no statistical differences in tensile strength, tensile modulus, and cell wall cross-sectional area were found between 4- and 6-yr-old bamboo fibers. However, statistical difference was found between 2-yr-old fibers and 4- or 6-yr-old fibers, indicating that bamboo maturity is about 4 yr. Table 3 also shows that properties are significantly different between mature and juvenile latewood fibers for Chinese fir.

Literature has shown the importance of single fiber extraction to preserve the original properties as much as possible. Methods of separating fibers have an effect on fiber strength. Peroxide, acid, and alkaline used for isolation in this research can degrade cellulose and hemicelluloses except for removing lignin in the middle lamellae depending on treatment conditions. Burgert et al (2002) compared effects of two fiber separation techniques on mechanical properties of single fibers: mechanically peeling out with tweezers and a chemical treatment with Jeffrey solution, which consists of 10% nitric acid and 10% chromic acid in water (Omolodun et al 1991). They found that nitric acid solution-treated fibers have much lower strength and stiffness than mechanically isolated fibers. Similarly, Chen et al (2011) reported that nitric acid agent accelerated maceration rate but decreased tensile strength of bamboo fibers. They also discovered that at least 35% of cell wall materials were removed during chemical maceration using a solution of hydrogen peroxide and acetic acid similar to the one used in this research (Burgert et al 2005). Cell wall cross-sections of chemically isolated fibers were significantly smaller than those of mechanically isolated fibers (Burgert et al 2005; Chen et al 2011). When tensile strength and modulus were calculated, differences were compensated for by greater shrinkage of chemically isolated fibers. Resultant tensile properties calculated for fibers were nearly identical between mechanical and chemical (hydrogen peroxide and acetic acid) isolation methods (Burgert et al 2005).

In this study, 5% NaOH solution was used to pulp kenaf fibers. The hydroxide ion (OH^-) mainly reacts with lignin, causing it to degrade into smaller soluble fragments. At about 100°C, hemicelluloses and amorphous cellulose chains start degrading through a peeling reaction at the reducing ends. Above 140°C, polysaccharide chains are cleaved by alkaline hydrolysis (Mossello et al 2010). However, findings were not consistent in the literature on the effect of mercerization on fiber mechanical properties. Sodium hydroxide probably decomposed polysaccharides to a larger extent than hydrogen peroxide and acetic acid solution. Hence, tensile strength and tensile modulus of bamboo fibers treated with 15% NaOH at 60°C were lower

than fibers treated with hydrogen peroxide and acetic acid solution (Chen et al 2011). Tensile strength and modulus of ramie fibers treated in 2% NaOH solution for 2 h decreased significantly compared with untreated ramie fibers (Munawar et al 2008). However, sisal fibers treated with 8% NaOH had a higher tensile strength and modulus than untreated fibers (Kim and Netravali 2010b). Edeerozey et al (2007) also reported that mercerization using a concentration up to 6% improved mechanical properties of kenaf fiber significantly compared with untreated kenaf fibers, whereas 9% concentration decreased tensile properties. The effect of 3% NaOH treatment on tensile modulus and strength of kenaf fiber bundles was not pronounced (Symington et al 2009). It was assumed that alkaline treatments would have a larger impact on fiber bundles than on individual fibers because hydroxide ions mainly attack pectin and lignin, which bond individual fibers into bundles. In this sense, it is assumed that the 5% NaOH solution used for kenaf retting in this project minimally affected mechanical properties of kenaf fibers.

Previous work has proven that measured tensile properties of Chinese fir wood fibers are in agreement with the literature (Wang et al 2011). Tensile properties of individual bamboo fibers measured in this study are compatible with experimental data (tensile strength and modulus: 1780 MPa and 27 GPa) reported by Chen et al (2011) using the same chemical isolation technique. To the best of our knowledge, no experimental data on tensile properties of individual kenaf and ramie fibers have been reported in the literature. However, data concerning tensile strength and modulus of bamboo, kenaf, and ramie fiber bundles can be found in several publications (Table 4). Comparison of Table 4 with Table 1 shows that tensile strengths of the three nonwood individual fibers were much higher than those of corresponding fiber bundles. This could be explained by two facts. One is that weak links exist in the fiber bundles, ie interfiber interface mainly consisting of pectin and lignin debonds more easily than fracture of fiber itself. The other is that tensile strength and modulus of fiber bundles in the referred publications listed in Table 4 were calculated on the basis of cell cross-sectional areas other than cell wall areas. Strength and modulus based on cell wall cross-sectional areas are larger than those based on cell cross-sectional areas (Burgert et al 2002). Also, tensile modulus of individual fibers is smaller than that of fiber bundles even when fiber bundle tensile modulus

Table 4. Tensile properties of fiber bundles from the literature

Fiber types	Tensile strength (MPa)	Tensile modulus (GPa)	Tensile strain (%)	Treatment conditions	Reference
Bamboo	482	34	—	Mechanical, N = 71	Shao et al 2010
	503	36	1.4	Mechanical, N = 5	Rao and Rao 2007
	341	20	1.7	Chemical degumming, N = 5	Rao and Rao 2007
	610	46	—	Derived, rule of mixture	Amada et al 1997
	810	55	—	Derived, rule of mixture	Nogata and Takahashi 1995
Kenaf	239	—	—	6% NaOH 3 h, N = 5	Edeerozey et al 2007
	215	—	—	Untreated, N = 5	Edeerozey et al 2007
	290	18	—	Growing at 20°C region	Ochi 2008
	600	39	—	Growing at 30°C region	Ochi 2008
	146	14	1.1	Bacterial retted, N = 30	Xue et al 2009
	473	34	2.0	Untreated, N = 25	Symington et al 2009
	419	35	1.4	3% NaOH 30 min, N = 25	Symington et al 2009
Ramie	621	48	1.9	N = 150	Lodha and Netravali 2002
	830	43	3.4	Untreated, N = 55-59	Munawar et al 2008
	554	21	3.9	2% NaOH 2 h, N = 55-59	Munawar et al 2008
	627	32	2.7	N = 50	Nam and Netravali 2006
	560	25	2.5	N = 20	Goda et al 2006

was calculated with a larger cell cross-sectional area (Table 4). Loss of the matrix (pectin, lignin, and hemicelluloses) caused by chemical isolation could account for the decrease of individual fiber tensile modulus. It is known that the filler in a composite increases the modulus of the composite (Ji et al 2002).

SUMMARY AND CONCLUSIONS

Characteristics of fibers from different publications are often compared to identify their applications. However, different publications used different techniques to measure these characteristics. In this study, similar techniques have been used to measure tensile properties of four types of fibers, enabling reliable comparison among fibers. Two-yr-old bamboo fiber had a larger cell wall cross-sectional area, larger elongation at break, and lower tensile strength and modulus compared with those of 4- and 6-yr-old bamboo fibers. No significant difference in fiber characteristics between 4- and 6-yr-old bamboo fibers suggests that bamboo reached maturity after 4 yr old. Juvenile latewood fibers had a lower cross-sectional area, larger elongation at break and MFA, and lower tensile strength and modulus than mature latewood fibers. The characteristics of fir fiber were widely distributed. Among tested species, bamboo fiber had the highest tensile strength and modulus and smallest cell wall cross-sectional area. Ramie had the largest cell wall cross-sectional area and elongation at break but lowest tensile modulus. Kenaf showed the lowest elongation at break, but other properties of kenaf were balanced. Moso bamboo fibers were much stronger and stiffer than most other fibers tested, indicating that bamboo fibers have potential in the production of high-performance fiber-reinforced composites.

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