Tensile and Bending Properties and Correlation of Windmill Palm Fiber

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Widely distributed in southern China, the windmill palm tree (*Trachycarpus fortunei*) is an important economic tree species from which palm fiber can be stripped. Palm Fiber (PF) is divided into palm leaf sheath fiber (PLSF) and palm petioles fiber (PPF), and both have good elasticity. These fibers can be used to produce mattresses and other elastic compound materials. While PLSF and PPF shared a similar elastic modulus, the elastic limit and elastic strain of PLSF were found to be significantly higher than that of PPF. Also, PLSF had superior tensile elastic properties. Within the elastic range, the bending and tensile properties of PF were almost the same. When given force under the horizonal-straight state, PLSF displayed superior bending elastic properties.

Keywords: Windmill palm fiber; Tensile; Bending; Properties; Correlation

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INTRODUCTION

Palm fibers (PFs) are stripped from windmill palm trees, which are widely distributed in southern China. Palm trees are tall and straight, with a beautiful shape. They are evergreen and are usually used as ornamental trees (Fig. 1(a)). The windmill palm trunk is upright with a cylindrical shape, and the lower part of the trunk is packed with leaf sheath fibers in a cross-mesh arrangement (Fig. 1(b)). PFs can be divided into palm leaf sheath fiber (PLSF) and palm petioles fiber (PPF), which depends on the position of extraction. The former is extracted from the leaf sheath sheet, while the latter is extracted from palm petioles (Fig.1 (c)).

PLSF is dark brown with a smooth and shiny surface (Fig. 2(a)). It feels supple and elastic and is much like hard hair. PLSF does not contain sugar and tannin, and it is known as the traditional PF. Because the output of PLSF is small, the price is high. It is estimated that a palm tree can only produce about 2 kg of PLSFs in a year. PPF is light brown (Fig. 2(b)). It feels rough, similar to hay. The yield of PPF is high, but it contains a little sugar and tannin. Thus, it is easy to grow mold and reproduce bugs. As a result, processed PPFs are often used to replace PLSFs. It is difficult to distinguish the two kinds of fibers from each other if people are not familiar with them.

Palm fibers are larger in diameter than other common natural fibers, with the majority ranging between 300 µm to 450 µm. Si particles coat the fiber surfaces. Palm fiber is round, with a great range of hollow and parallel single fibers linked with each other tightly; thus, palm fiber is a unidirectional composite. The typical stress-strain curve shows a yield and contains three main parts. Regarding the tensile properties, both the fiber strength and breaking strain decrease, whereas Young's modulus increases with the increase of gauge length. During loading, the alternating orientation of fibrils results in a distinctive tensile behavior (Guo 2014).

Fig. 1. (a) Palm tree panorama; (b) palm tree trunk stripped leaf; (c) sheath wrapped around palm trunk

Fig. 2. (a) Palm leaf sheath fiber; (b) palm petioles fiber

Palm fiber is a natural fiber with big, uneven diameter ranging from 99 µm to 539 µm, and mostly from 250 µm to 400 µm. The range of values of rupture strength, Young's modulus, and rupture elongation during fracture tensile testing are 89 to 222 MPa, 0.44 to 1.09 GPa and 14.68 to 23.45%, respectively. Thus, palm fiber has medium strength and high elongation (Li 2012).

According to its direction and size, fibers from every piece of leaf sheath are separated into three layers. The mean diameters of fiber bundles from one sheet, which are separated into inside, middle, and outside layers, are 202.1 µm, 418.0 µm, and 342.5 µm, respectively. The diameter of fiber bundles ranges from 147 to 547 µm (Zhai 2010).

Palm leaf fiber possesses good softness. There are some clear vertical stripes found lengthwise, and there are also many pores and nodes. The cross section shows an irregular dentate shape with a compact structure, which has a lot of small openings (Liu and Mao 2006).

When used, PF products bear complex external forces, such as tensile, compression, bending, and torsion. However, as a linear material with a long and thin form, longitudinal tensile is the main form of stress for PF. The textile fiber method is used to test the properties of fiber; this method uses a universal testing machine to stretch fibers vertically with a certain speed. In this way, the tensile property parameters (TMPP) of fiber material, including elastic modulus, elastic limit, elastic strain, tensile strength, and elongation after fracture, are obtained.

Unlike textile fibers, which are widely used in textile fabrics, windmill palm fiber is often used in elastic composites such as mattresses. Palm fiber composites are more resilient when bent, so the obtained tensile property parameters (TPP) could not be directly used on the research of elastic property of mattress and the similar materials. But there is relationship between tensile property (TP) and bending property (BP). Because the test to obtain the TPP is easy to operate, bending property parameters can be derived from tensile property parameters of PF. TP was first researched in the literature, and a theoretical correlation between tensile and bending was derived in the present work. A formula was established so that the correlation between TP and BP could be demonstrated by testing the tensile properties of palm fiber.

EXPERIMENTAL

Materials

Raw PFs (PLSF and PPF) were provided by DaZiRan Science & Technology Co., Ltd. (Guiyang, China). The selected PFs had no joints or defects. The fineness was 40 to 60 tex, and the length was over 150 mm.

PFs were conditioned to an equilibrium moisture content at 25 °C and 50% to 60% humidity. The absolute water content of PLSF and PPF was between 12% and 13%, which was tested by the drying method.

Methods

A total of 50 specimens of each form (PLSF and PPF) were selected. The tensile property parameters such as elastic modulus, elastic strength, and elastic deformation in elastic deformation period were obtained by tensile testing. The theoretical bending property parameters were calculated through tensile property parameters by analysis. Next, fiber specimens of the same specification were selected for bending tests to obtain the bending property parameters. Finally, the correlation between tensile and bending property parameters was demonstrated.

Tensile Test

To ensure that PF specimens had similar characteristics, the final test specimens of fiber were chosen to be more representative and were similar to each other in form.

Tensile testing was performed on a Shimadzu universal mechanical testing machine (Fig. 3(a)) (Shimadzu AGS-X20KN, Kyoto, Japan). The length of fiber specimens was 70 mm, which represented 50 mm of valid clamping length and some gripper allowance. The speed of machine was set at 20 mm/min. Latex was used on the clamp surface to avoid slipping, and according to former experiment, its effort of avoid slipping was proved great (Fig. 3(b)). During the test, fiber specimens were fixed on the central line of the clamping device.

To ensure that the data were valid, data were included only if the fractured part of the test specimen was between the grippers. A total of 50 valid measurements were collected for each sample group.

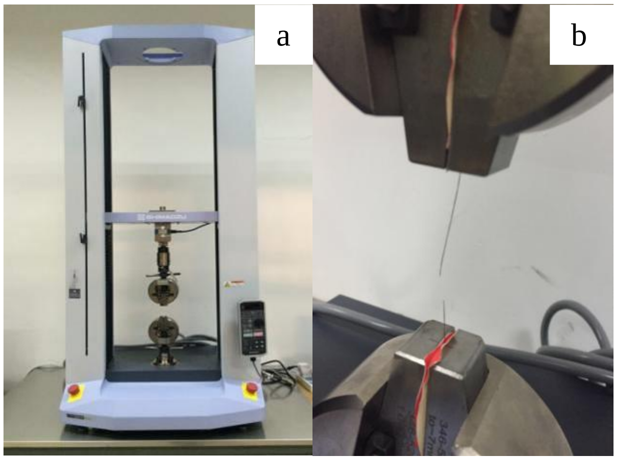

Fig. 3. (a) Shimadzu universal mechanical testing machine; (b) fixture improvements

Bending Test

Bending tests of palm fiber were performed on a bending elasticity tester of PF, (Fig. 4) (Liu *et al.* 2015). First, a micrometer was moved down to touch PF, which indicated elasticity. The reacting force of the elasticity was displayed on the electronic scale in the form of mass. The micrometer and electronic scale were tared at the beginning of the test. The bending property was calculated from the corresponding relationship between micrometer displacement and mass changes.

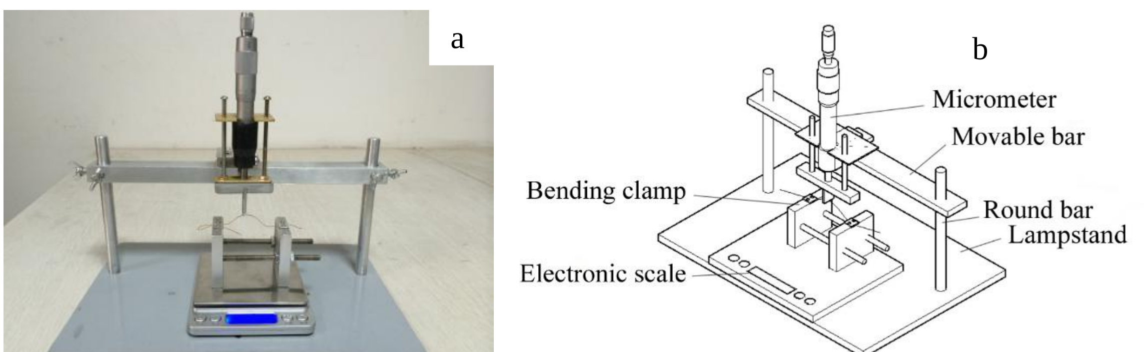

Fig. 4. (a) Bending elasticity tester of palm fiber; (b) structural perspective for bending elasticity tester of palm fiber

During the tensile test, the valid clamping length was 50 mm, and the speed was 20 mm/min. The same values were used for the bending test. First, fiber specimens were fixed on clamps, with each side being 10 mm. The valid length of the specimen was 50 mm. The specimen was oriented in a horizontal straight state, and the horizontal tensile force was zero.

As the micrometer was operated by a human, a fixed operator was requested to move the micrometer at a steady speed. The speed of the micrometer was about 20 mm/min.

RESULTS AND DISCUSSION

Analysis of Phenomenon of Fiber Tensile Failure

Forms of tensile failure

There were mainly two forms of tensile failure: brash tension and splinter tension. Brash tension, as shown in Fig. 5(a) and Fig. 6(a), means regular brash at the fiber break part of fiber. Splinter tension, shown in Fig. 5(b) and Fig. 6(b), means an irregular splinter at the fiber break. As shown in Table 1, brash tension was the main form of tensile failure for PF and PLSF.

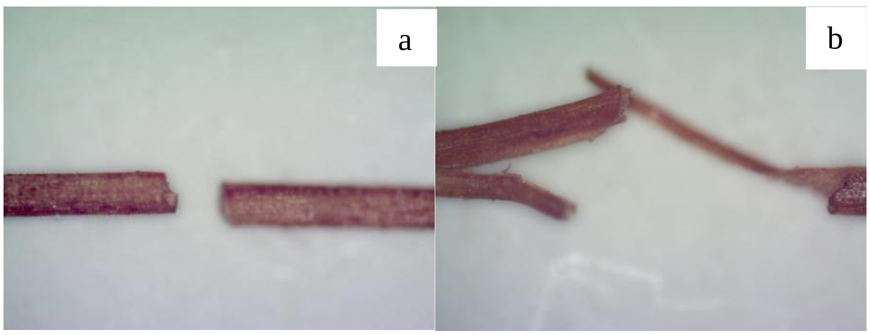

Fig. 5. Failure modes of palm leaf sheath fiber. (a) Brash tension; (b) splinter tension

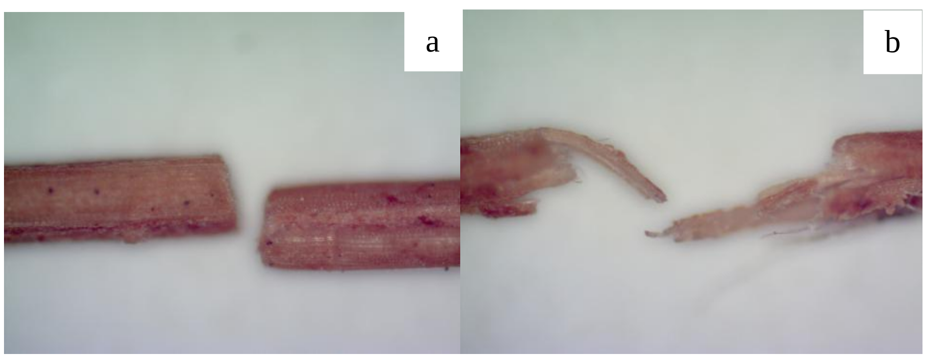

Fig. 6. Failure modes of palm petioles fiber. (a) Brash tension; (b) splinter tension

Location of tensile failure

According to Saint Venant's Principle, failure usually occurs between the middle parts of fiber (Toupin 1965); otherwise, the data would be invalid. Table 1 lists the number of forms of failure and position of tensile failure. There were failures in every position of the middle part of the fiber.

Table 1. Amount of Failure Mode and Position for Palm Fiber Tension

Species	Failure Modes			Failure Positions			
	Splinter	Brash	Total	Near holder	Center effective	Other effective	Total
PLSF	8	42	50	13	14	23	50
PPF	21	29	50	10	19	21	50

Analysis of the Tensile Test

Analysis of stress-strain of PF tensile

Figure 7 shows typical palm fiber tensile stress-strain curves. The test was ended after the tensile fracture of PLSF and PPF. The whole process of tensile straining included elastic-deformation and inelastic-deformation.

(1) Part oe, the oblique line oe, was the elastic-deformation, which was in accordance with Hooke's Law. The stress value, which corresponded to point e, was called the proportional limit. Within the elastic limit, stress and strain had a linear relationship. Hence, when removing the force and stop tensile, the deformation of specimen would disappear and recover to the original situation.

(2) Part eb, the oblique line eb, was inelastic-deformation. After point e, the fiber began to yield, but it was not obvious. In this stage there were non-linear characteristics between stress and strain, such that the specimen could not recover to its original situation. Fibers that could recover entered the plastic deformation stage. This was attributed to the special structure of PF; especially, the orientation of microfibrils in the fiber secondary cell wall changed, which functioned as enhancing material. The change resulted in the rearrangement of the non-crystalline region in the fiber consisting of a semi cellulose and a cellulose. Finally, the orientation microfibril broke if the machine continued to speed up.

The stress value which that corresponded to Point b was called tensile strength. The corresponding stress was almost equal to tensile strength. Though Point b and Point b' were based on different definitions, the tensile results were similar. Thus, the stress and strain values corresponding to b were chosen as the tensile strength and limit strain. In addition, tensile strength and elongation after fracture were chosen to measure the tensile bearing capacity and deformation property index.

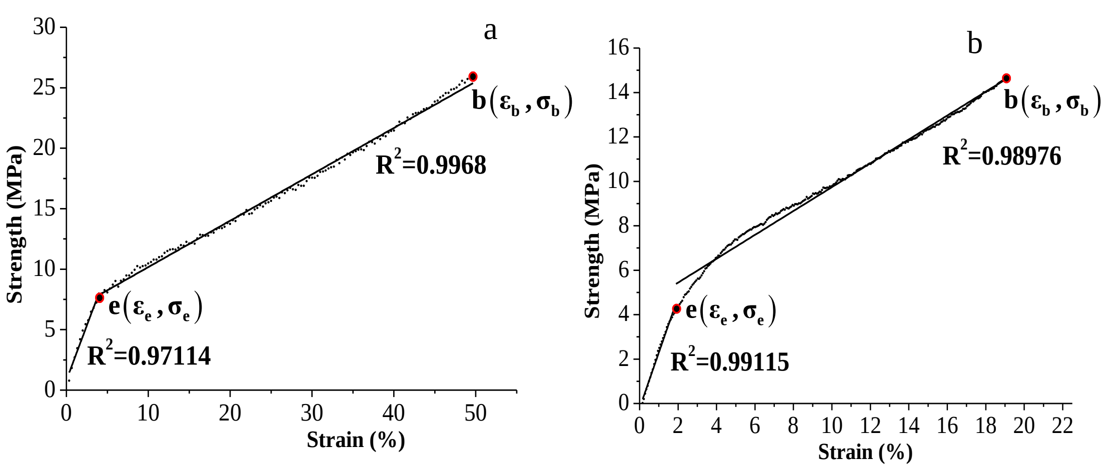

Fig. 7. Tensile stress-strain curves of (a) palm leaf sheath fiber and (b) palm petioles fiber

The constitutive relation of PF tensile

According to the PF stress-strain curves, two typical constitutive relations of the two fibers were formed in terms of elastic-deformation and inelastic-deformation.

Table 1(a). Constitutive Relation of PLSF

ε	σ	R^2
$0 \leqq \varepsilon \leqq \varepsilon e$	1.80828ε+0.82674	0.97114
$\varepsilon e \leqq \varepsilon \leqq \varepsilon b$	0.3835ε+6.3349	0.9968

Table 1(b). Constitutive Relation of PPF

ε	σ	R^2
$0 \leqq \varepsilon \leqq \varepsilon e$	2.49252ε+0.20104	0.99115
$\varepsilon e \leqq \varepsilon \leqq \varepsilon b$	0.53719ε+4.3672	0.98976

Results of tensile test

As shown in Table 2, the elastic modulus of PF and PLSF were almost equal. In terms of elastic limit and elastic straining, PF was superior to PLSF. Moreover, the tensile strength at break and percentage elongation after fraction of PF were larger than in PLSF. Thus, PF was superior to PLSF in both elastic and tensile properties.

Table 2. Comparison for Tensile Elasticity Index of Palm Leaf Sheath Fiber and Palm Petioles Fiber

Species	Tensile Index									
	Elastic limit (MPa)	Cov %	Elastic strain (%)	Cov (%)	Elastic modulus (MPa)	Cov (%)	Tensile strength (MPa)	Cov (%)	Elongation after fracture (%)	Cov (%)
PLSF	32.14	26.11	1.24	27.82	1948.74	24.35	79.42	29.31	10.83	21.67
PPF	21.11	17.08	0.72	24.35	2039.41	22.82	64.95	20.11	9.15	25.08

Note: Cov is the short term for covariance.

In PF, the content of extracts, ash, lignin, cellulose, and hemicellulose were 1.44%, 0.435%, 36.93%, 38.79%, and 10.89%, respectively. In PLSF, the corresponding values were 0.96%, 2.56%, 28.80%, 38.89%, and 13.79%, respectively (Liu 2016). The two fibers have similar contents, with the exception of lignin. Lignin is crucial to hardness. Lignin probably causes the difference in properties between two kinds of fibers.

Initial Establishment of the Theoretical Relationship between Tensile and Bending of Palm Fiber

The relationship between the tensile and bending straight state of palm fibers

PF was fixed on the central line of the clamping device, and the span was set 50 mm. In a simulated experiment, in the phase of elastic-deformation, the central Point O was under a concentrated force, and press shift was produced, as shown in Fig. 8(a).

As shown in Fig. 8(b), in the process of being pressed, PF was only forced by axial tensile stress. In the linear phase of tensile elasticity, the bottle margin span of isosceles triangle ΔOMN, which can also be looked as the length of segment MN, is 1. When the speed, size of specimen, and material were the same, the tensile property values can be measured and circulated. According to the force diagram in Fig. 8(b), the tension force T is the resultant of T_y in vertical and T_x in horizontal. Its stability is achieved by the balance of force.

The diameter of a single fiber was about 3.5*10^{-4} m; moment of inertia $I = \frac{\pi D^4}{64}$, the with a unit number of 10^{-16}; its rigidity was $K = E \cdot I$. The stiffness in bending of single fiber is almost zero, *i.e.*, there was no stiffness detected. Considering that the materials will be used to produce mattress and elastic buffer products, and that a single fiber has no detectable stiffness, it is difficult to test tensile properties by general methods. The machine, whose patent number is ZL 2015 2 107629.6, was used to solve this problem (Liu *et al*. 2015)

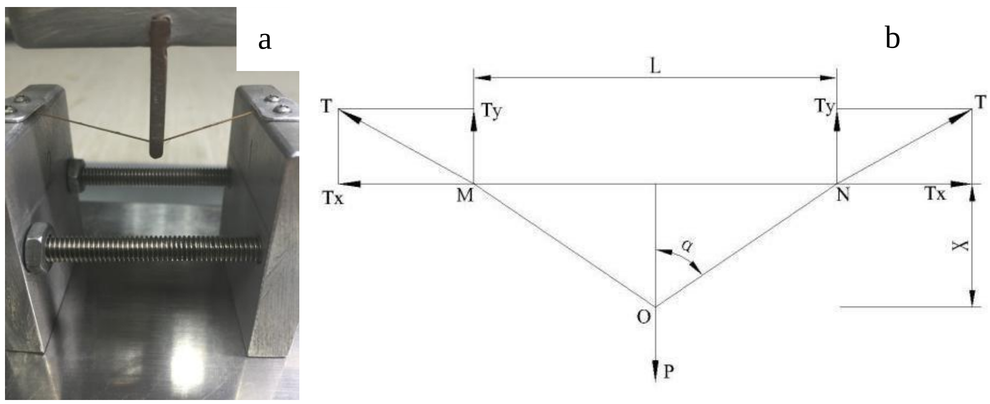

Fig. 8. (a) Schematic diagram and (b) force diagram for bending load of palm fiber

According to Fig. 8(b), the tension force T is the resultant of Ty in vertical and T_x in horizontal,

$$T_{\mathbf{y}} = T \times \mathbf{cos}\alpha \tag{1}$$

According to the force balance principle, $\sum F_y = 0$,

$$2T_y - P = 0 \Rightarrow P = 2T_y = 2T\cos\alpha \tag{2}$$

$$T = \frac{P}{2\cos\alpha} \tag{3}$$

Assuming that elastic deformation of PF within the scope of elastic deformation is ε, the length of OM and ON can be calculated by the following formulae.

$$OM = ON = \sqrt{\Delta^2 + (\frac{L}{2})^2} \tag{4}$$

$$\cos\alpha = \frac{X}{OM} = \frac{X}{\sqrt{\Delta^2 + L^2}} \tag{5}$$

Stress and strain were calculated as follows.

Stress $$\sigma = \frac{T}{S} = \frac{P}{2S \times \cos a} = \frac{P \times \sqrt{\Delta^2 + (\frac{L}{2})^2}}{2S \times X} \quad (6)$$

Strain $$\varepsilon = \frac{\Delta L}{L} = \frac{OM - L}{L} = \frac{\sqrt{\Delta^2 + (\frac{L}{2})^2} - L}{L} \quad (7)$$

According to the stress-strain relationship curve, the elastic limiting point of PF was found, and the elasticity modulus was calculated as follows,

$$E = \frac{\sigma}{\varepsilon} = 2SX\left(\sqrt{X^2 + (\frac{L}{2})^2} - L\right) \quad (8)$$

where L (mm) refers to span of fiber, X (mm) refers to displacement, P (N) refers to tensile limit, and S (mm^2) refers to fiber cross-sectional area.

Elasticity theoretical index for tensile and bending elasticity index of palm fiber

According to Tables 3 and 4, the testing results of bending and tensile were very close, and elastic index was even closer. There was a big difference between breaking strength and breaking elongation, which is the result of shear force and other factors. Under the condition without stressing force and three-point loading, tensile properties can be tested by testing the tensile properties of one fiber. Furthermore, the data also established the correlation between tensile and bending properties.

Table 3. Comparison for Bending Elasticity Index of Palm Leaf Sheath Fiber and Palm Petioles Fiber

Bending Index	Species	
	PLSF	PPF
Elastic limit (MPa)	31.18 (27.82)	20.46 (24.6)
Elastic strain (%)	1.18	0.68
Elastic modulus (MPa)	1808.74	2254.42
Bending strength (MPa)	66.8	61.93
Elongation after fraction (%)	11.9	9.7

Note: Cov (%) values are shown in parentheses.

Table 4. Test Result Ratio of Tensile and Bending Strength of PLSF and PPF

Species	Test result ratio				
	Elastic limit (MPa)	Elastic strain (%)	Elastic modulus (MPa)	Bending strength (MPa)	Elongation after fraction (%)
PLSF	1.03	1.05	1.08	1.19	0.91
PPF	1.03	1.06	0.90	1.05	0.90

CONCLUSIONS

1. Palm fibers are divided into palm leaf sheath fibers (PLSF) and palm petioles fibers (PPF), depending on the position of the extraction. The PLSF are extracted from the leaf sheath sheet, while the PPF are extracted from palm petioles. The PLSF is dark brown with a smooth and shiny surface. Its surface is supple and elastic, similar to hair. Palm petioles fibers are light brown, and the material feels rough and similar to hay.
2. Brash tension was the main form of tensile failure of PFs. The elasticity modulus of PLSF and PPF were similar, but that of the former was smaller. The elastic limit and elastic elongation of PLSF was bigger than that of PPF, so PLSF was superior to PPF in terms of elastic properties.
3. In the elastic range, the tensile and bending properties were almost the same under the straight condition, both of which were accordance with Hooke’s Law. After comparing the test data to the theoretical data of bending testing, the error was about 5%, which was comparatively small. Thus, tensile strength contributed to the structure stability of palm fiber in bending in the elastic stage. The testing data also confirmed the relationship between tensile and bending properties.

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