Mechanical Behavior Study of Bending and Compression of Pineapple Leaf Fiber

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Abstract. This study aims to provide new-type textile raw materials for the textile industry with pineapple leaf fiber as an example. The bending of pineapple leaf fiber and compressibility of fiber assemblies were tested with JXW03 single fiber compression bending tester and KES-G5 minitype compression apparatus respectively, to study the change rule of bending property of pineapple leaf fiber and represent the compression characteristic curve of fiber assemblies. The results indicate that the values of $E_B$ and $R_B$ of fiber roots are 6.43GPa and 294.59E-5cN·cm$^2$, and that of the middle segment of fiber are 2.82GPa and 118.17E-5cN·cm$^2$; the mean values of $R_c$, $\Delta T$ and $L_c$ of fiber roots are 57.73%, 4.33 mm and 0.46, and that of the middle segment of fiber are 62.20%, 4.65 mm and 0.43. Anova suggests that there exists highly significant difference in the sampling site in respect of equivalent bending modulus and flexural stiffness of fiber ($P<0.01$), no significant difference in respect of compressive mechanical indicators of fiber assemblies ($P>0.05$), the compression-restore curve of fiber roots and that of central assemblies are in the same shape, and they are similar in respect of compression recoverability, besides, the compression curve doesn’t coincide with restoration curve for fibers are of elasticity and viscosity concurrently.

1. Introduction

Pineapple, also referred to as ananas comosus, falling into bromelia of pineapple family, and being perennial monocotyledon, is a famous tropical fruit in the world[1]. In China, pineapple is widely planted in Guangdong, Hainan, Guangxi, Yunnan, Fujian and Taiwan, and its planting area in recent years has been staying around 70000 hm$^2$. 666.7 m$^2$ pineapple leaves weigh about 5~10 t, and the total output of pineapple leaves throughout the country is approximately 10,000,000 t/y, which causes a lot of resource waste and ecological environment pollution[2]. The fiber content in pineapple leaf is only 1.5% or so (dry basis). Pineapple leaf fiber is leaf fiber, multicellular bundle fiber formed by gloea adhesion, and the six generation of natural fiber[3] following cotton, woolen, silk, bast fiber and raw bamboo fiber. As people’s awareness of environmental protection and health is enhanced, natural fiber fabric attracts more and more attention.

Pineapple leaf fiber is a type of flexible material, and will be subject to bending torsion and compression at different temperatures and humidities for making textiles for subsequent degumming and textile processing. The bending property of fiber is likely to degrade due to fatigue, which will even lead to collapse of material in severe cases;
compression property requires fiber to be resistant to exoteric force to a certain extent, because fiber compression will directly impact its interior porous structure to change its interior air content and affect its heat retaining property; fiber is required to be with filling function if used as thermal insulation material, so the compression property and recoverability of plant fiber must be taken into consideration\(^{[5-6]}\).

In general, the mechanical behavior of bending and compression of fiber can be regarded as exoteric force on fiber in different directions. The compression property of fiber is one of the physical and mechanical properties of fiber, and is formed by resultant force of bending and local stretch, torsion, friction, glide and compression of fiber. The component forces are correlative to each other to a certain extent. Study on the bending and compression properties of single fiber of plant fiber used as textile material is of little significance. Pineapple leaf fiber is multicellular bundle fiber formed by multiple unicellular fibers adhered via gloea. Its fiber fineness is of significant difference and it is flexible, so the sample preparation is difficult. Thus, the bending property of fiber is mainly evaluated by measuring bundle fiber. Both textile materials and finished textile fabrics can be regarded as fiber assemblies. The compression property of fiber assemblies will affect the usability of final fiber products and the processing, use, storage and transportation of textile products. Therefore, it is more helpful to reflect the main physical property indicators\(^{[7]}\) of materials by studying compression property of fiber assemblies.

2. Test material and method

2.1 Test material

Kayin pineapple leaves from the pineapple planting base in Xuwen county of Zhanjiang city were selected for the experiment. Self-developed fiber extractor was employed for extracting fiber from pineapple leaves. The extracted fibers were washed and dried to obtain pineapple leaf fiber. The fibers were carded. Root and central segments were taken based on difference in fiber fineness, and were numbered and put in two sample bags. The carded root (central) fibers were cut out 30mm long segments as test pieces with cutter with the middle part cut method.

2.2 Sample preparation

2.2.1 Preparation of bent samples

30 pieces of fiber were sampled from each bag, and divided into 3 groups averagely. The fibers were pasted on cardboard (3.5 mm×1 mm) with one end reaching out of the long edge of cardboard by a length 10~100 times of fiber diameter (about 2 mm in general) in straight and upright state, for bending property measurement. The finished fiber needle sample is as shown in Figure 1.

2.2.2 Production of compression test

2g fibers were taken out from the test bag with the aid of FA2004 electronic analytical balance (precision 0.0001 g) and horizontally spread in a rectangular paper box (30 mm×30 mm×15 mm) uniformly. The paper box is uncovered, consists of a bottom and four walls only, and is with a quadrate hole (20 mm×20 mm) at the bottom. The paper box can ensure horizontal spreading of fibers. In the test process, fibers didn’t separate from the paper box. For testing, the hole at the bottom is opened, and compression test is conducted only for the fiber bundle exactly above the hole. The paper box has no influence on the thickness of fiber assemblies or the measured pressure. With the abovementioned method, 3 boxes of samples of root fiber and 3 boxes of samples of central fiber have been prepared respectively. The finished samples are as shown in Figure 2.
2.2.3 Test apparatus
Test apparatuses include superfine pointed tweezers, scalpel, black cardboard, marking pen, double faced adhesive tape, glass ware, straightedge (300mm L, precision 1 mm), sample bag, pencil, scissors, fiber specimen cutter, FA2004 electronic analytical balance (precision 0.0001g), JXW03 single fiber compression bending tester, and KES-G5 minitype compression apparatus.

2.3 Test method

2.3.1 Bending property test of fiber
JXW03 single fiber compression bending tester developed by Textile Materials & Technology Laboratory of Donghua University is employed for the test, and the Euler load principle[8] of single fiber compression bending model with lower end of fiber needle held and upper end hinged is conformed to. Fiber bending test is conducted under constant temperature (22±2℃) and constant humidity (65±5%RH). The samples pasted on the cardboard are clipped with metal clips of test apparatuses for fixation, fiber position is adjusted to make the head end of fiber is located on the centre point of the circular sheet metal (namely the loading end of slightly pitted sensor) as far as possible, the speed of the platform below apparatus moving up is set to be 0.01 mm/s, and data is measured and recorded. Fiber needle moves from bottom to top, the test is stopped until the critical value is reached, and the measured data is saved. In the test process, apparatus is set to take pictures once every 10s.

2.3.2 Compression property test of fiber
Compression test of fiber assemblies is conducted under such conditions of indoor temperature of 22±2℃ and relative humidity of 65±5%RH. KES-G5 minitype compression apparatus is employed. A cylindrical detection pressure head with maximum pressure of 50 gf/cm², compression speed of 0.5 mm/s and cross sectional area of 2 cm² is adopted. The compression probe squeezes fiber assembly samples downwards at the speed of 0.5 mm/s, and moves up to home at a constant speed of 0.5 mm/s immediately after the maximum pressure of 50 gf/cm² is achieved. The following data is recorded with computer in real time, including compressive stress P per unit area of sample, compression thickness T of fiber, compressive stress P' per unit area of fiber assembly during restoration process and compression thickness T of fiber, and corresponding relation curves are developed on this basis[9].

2.4 Data measurement and calculation[10]

2.4.1 Bending property indicators of fiber
Formulas (1) and (2) are designed for computation of pineapple leaf fiber needle. Via the test, the length value and diameter value can be measured with optical microscope.
$$L_0 = \sqrt{(x_1-x_3)^2-(y_1-y_3)^2}$$

(1)

$$D = \sum_{i=1}^{n} D_i/n$$

(2)

Wherein: 1) \((x_1, y_1)\) and \((x_3, y_3)\) refer to coordinates of hinge endpoint and holding endpoint of single fiber needle respectively;

2) \(D_i\) refers to diameter of any point on fiber needle of a length of \(L_0\), and \(D\) to average diameter of fiber needle;

3) \(n\) refers to number of points taken for equidistance measurement on fiber needle of a length of \(L_0\), which is generally larger than 10.

Flexural stiffness \((E_B I)\) represents bending resistance of fiber, is used for describing stiffness or softness of fiber, and is codetermined by essential bending factor (bending modulus \(E_B\)) and cross section factor (diameter \(D\) and shape of cross section). Based on the experimental principle of JXW03 single fiber bending tester, namely Euler critical load principle, the corresponding critical load formula can be obtained, as below:

$$P_{cr} = (kL^2)(E_B I/L^2) = 20.19E_B I/L^2$$

(3)

Wherein, \(E_B\) refers to equivalent bending modulus, which is obtained via integral mean of compression modulus and tensile modulus; \(E_B I\) refers to flexural stiffness of fiber.

Like cross section of most natural fibers, the cross-sectional shape of pineapple leaf fiber is approximately circle with obvious long axis and short axis. Therefore, a cross-sectional shape coefficient indicating difference between long axis and short axis is was introduced into the calculation of critical load. According to mechanics of materials, the minimum moment of inertia of perfect circle is

$$I_0 = \pi r^4/4 = \pi D^4/64 \ (r = D/2)$$

(4)

Thus, formula (3) is transformed into:

$$P_{cr} = 20.19E_B \phi I_0/L^2 = 20.19\pi^4E_B \phi/(4L^2) = (0.99E_B \phi)D^4/L^2$$

(5)

Wherein, \(P_{cr}\) refers to critical bending load of single fiber; \(L\) refers to protrusion length of fiber; \(I_0\) refers to moment of inertia of cross section; \(E_B\) refers to equivalent bending modulus; \(E_B \phi I_0\) refers to flexural stiffness of fiber; \(\phi\) refers to section factor.

According to formula (5), critical load of fiber is in linear relationship with the square of the ratio of cross section to length \((D^4/L^2)\), so the equivalent bending modulus \(E_B\) of fiber can be solved via the slope \(K=0.99E_B \phi\) of formula (5), the moment of inertia of cross section of fiber can be solved with inertia moment formula of cross section, and the flexural stiffness \(R_B\) of fiber can be solved on this basis.

$$E_B = \frac{1.01 \times 10^{-8}K}{\phi}$$

(6)

$$R_B = E_B \phi I_0$$

(7)

2.4.2 Compression property indicators of fiber

(1) Work \(W_c\) and compression-restoration work \(W_c'\) \((\text{N} \cdot \text{cm} \cdot \text{cm}^2)\). \(W_c\) means work of external force on fiber assemblies of unit area in compression process, and is equal to the area below P-T curve. Large value of compression work indicates that the assembly is fluffy. \(W_c'\) means work of pressure \(P'\) on assembly in restoration process of assembly, and is equal to the area below \(P'\)-T curve.

$$W_c = \int_{T_0}^{T_m} PdT$$

(8)

$$W_c' = \int_{T_0}^{T_m} P'dT$$

(9)
(2) Compression restoration rate $R_c$ (%). $R_c$ is percentage of compression restoration work to compression work, and represents compression restoration property of fiber assembly. Large value of compression restoration rate means good compression recoverability of assembly.

$$R_c = \frac{W_c}{W_c} \times 100\%$$  \hspace{5cm} (10)

(3) Linearity $L_c$ of compression curve. $L_c$ refers to the degree of buckling of compression curve of sample, namely the degree of closeness of curve to straight line in compression-restoration curve chart. Its value is the ratio of the area below compression curve to the area below the connecting line of the two endpoints of the curve. It represents the complexity of fiber assembly being compressed. The larger the value is, the more difficult compression is. In the formula, $P_m$ is 50 gf/cm$^2$.

$$L_c = \frac{2W_c}{P_m(T_0 - T_m)}$$  \hspace{5cm} (11)

(4) Compression thickness $T_0$ and $T_m$ (mm). $T_0$ is the thickness of fiber assembly under pressure of 0.5 gf/cm$^2$, namely the initial thickness; $T_m$ is the thickness of fiber assembly under maximum pressure $P_m$ of 50 gf/cm$^2$.

(5) Variation of compression thickness $\Delta T$ (mm) represents variation of the thickness of fiber assembly in compression process of assembly. Large value of variation of compression thickness means great loss of internal air void of fiber assembly in compression process.

$$\Delta T = T_0 - T_m$$  \hspace{5cm} (12)

3. Result and analysis

3.1 Bending property analysis of pineapple leaf fiber
JXW03 single fiber compression bending tester is adopted, and the shape and size of fiber needle are as shown in Table 1.

| Sample        | Specimen count | Diameter range/μm | Average diam/μm | Length range/mm | Mean length/mm |
|---------------|----------------|-------------------|-----------------|-----------------|----------------|
| Fiber root    | 30             | 46.35–82.05       | 60.86           | 1.82–2.42       | 2.14           |
| Fiber middle  | 30             | 35.05–92.06       | 59.52           | 1.69–2.45       | 2.17           |
Figure 3. Relation curve of critical load $P_{cr}$ of root and middle part of pineapple leaf fiber and $D^4/L^2$ and regression equation

Straight slope $K$ is obtained via regression of the curve shown in the figure based on the linear relation between critical load $P_{cr}$ of fiber and $(D^4/L^2)$. The cross section of pineapple leaf fiber is oval, the average bending section factor is $\varphi = b/a = 0.68$, and the values of long and short axes (a-long axis, b-short axis) of cross section are measured with biological microscope. Thus, with formulas (4), (6) and (7), the equivalent bending modulus $E_B$ and flexural stiffness $R_B$ of pineapple leaf fiber are solved, and the result is as shown in Table 2. Experiment is conducted to study the influence of sampling site of pineapple leaf fiber on bending property indicators. Anova suggests that highly significant difference exists in equivalent bending modulus and flexural stiffness due to sampling site of fiber ($P<0.01$), as shown in Tables 3 and 4.

Table 2. Bending data of pineapple leaf fiber

| Specimen      | Critical load range/(10^{-5}N) | Sample number | Equivalent bending modulus/(GPa) | Mean value of equivalent bending modulus/(GPa) | Flexural stiffness/$(10^{6} \text{N} \cdot \text{cm})$ | Mean value of flexural stiffness/$(10^{3} \text{N} \cdot \text{cm}^{2})$ |
|---------------|-------------------------------|---------------|----------------------------------|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|
| Fiber root    | 878.91~3332.14                | 1             | 6.53                             | 6.43                                          | 299.12                                       | 294.59                                         |
|               | 14                            | 2             | 6.83                             |                                              | 312.72                                       |                                               |
Table 3. Anova of equivalent bending modulus $E_B$

| Source of difference | Sum of squares | Freedom | Mean square | F value | P value |
|----------------------|---------------|---------|-------------|---------|---------|
| Sampling site        | 107.94        | 1       | 107.94      | 245.49  | 2.75E-07|
| Interactive          | 17.11         | 1       | 17.11       | 38.92   | 2.49E-04|
| Inside               | 3.52          | 8       | 0.44        |         |         |
| Total                | 128.57        | 10      |             |         |         |

Table 4. Anova of fiber flexural stiffness $R_B$

| Source of difference | Sum of squares | Freedom | Mean square | F value | P value |
|----------------------|---------------|---------|-------------|---------|---------|
| Sampling site        | 258814.32     | 1       | 258814.32   | 304.12  | 1.20E-07|
| Interactive          | 41280.22      | 1       | 41280.22    | 48.51   | 1.17E-04|
| Inside               | 6808.29       | 8       | 851.04      |         |         |
| Total                | 306902.82     | 10      |             |         |         |

3.2 Compression property analysis of pineapple leaf fiber

KES-G5 minitype compression apparatus is adopted to compress assemblies of roots and middle part of pineapple leaf fiber respectively, and the compression curves are as shown in Figure 4 and Figure 5.

Figure 4. Compression-restoration curve of roots of pineapple leaf fiber aggregation

Figure 5. Compression-restoration curve of assembly of middle part of pineapple leaf fiber

Analysis of compression-restoration curves shown in Figure 4 and Figure 5 suggests that compressing force $P$ in unit area increases as compression thickness $T$ decreases, and compression stops until the maximum pressure value of 50 gf/cm$^2$ is reached. After this, compression probe starts to rise again, and fiber assembly starts to rebound under the effect of fiber elasticity. With the restoration of fiber assembly, its thickness $T$ increases, and compressing force $P$ in unit area decreases but is less than that of corresponding thickness on the compression curve. This is because fiber is of viscosity, so that restoring force is less than compressing force of corresponding thickness, and restoration curve doesn’t coincide with compression curve[[1]].
Table 5. Compression property indicator of root and middle part of Pineapple leaf fiber

| Sampling site | Sample number | Compressive work (Wc)/(cN·cm²) | Compressive restoration work/(cN·cm²) | Compressive restoration rate/% | Compressive thickness variation/mm | Mean value of variation of compressive thickness/mm | Compressive thickness/mm | Linearity of compression curve | Mean Linearity of Compression Curve |
|---------------|---------------|--------------------------------|--------------------------------------|-------------------------------|----------------------------------|---------------------------------------------|-----------------------|-----------------------------|----------------------------------|
| Fiber root    | 1 #           | 4.90                          | 2.48                                 | 50.60                         | 4.45                            | 0.34                                       | 0.45                  |                             |                                  |
|               | 2 #           | 4.90                          | 3.08                                 | 62.80                         | 4.27                            | 0.60                                       | 0.47                  |                             |                                  |
|               | 3 #           | 4.90                          | 2.93                                 | 59.80                         | 4.26                            | 0.68                                       | 0.47                  |                             |                                  |
| Fiber middle  | 1 #           | 4.90                          | 3.12                                 | 63.60                         | 4.46                            | 0.41                                       | 0.45                  |                             |                                  |
|               | 2 #           | 4.90                          | 3.19                                 | 65.20                         | 4.82                            | 0.04                                       | 0.41                  |                             |                                  |
|               | 3 #           | 4.90                          | 2.83                                 | 57.80                         | 4.67                            | 0.24                                       | 0.43                  |                             |                                  |

According to Table 5, the means of Rc, ΔT and Lc of fiber root are 57.73%, 4.33 mm and 0.46, and that of middle part of fiber are 62.20%, 4.65 mm and 0.43, respectively. According to Tables 6, 7 and 8, the compression mechanical property of root and middle fiber assembly is of no significant difference (P>0.05). This is because although the main deformation form of plant fiber assembly under unidirectional compression is compression deformation, bending and shear deformation also exists since single fibers of fiber assembly will cross each other under compression. Meanwhile, friction and glide also occur among single fibers. Thus, the characteristics of single fibers are relatively ignored when compression property of fiber assembly is discussed[5].

4. Discussion

Through testing and analyzing bending and compression of different sampling sites of pineapple leaf fiber, studying bending and compression properties of root and middle part of fiber and fiber assembly, and analyzing the influence of different sampling sites on bending and compression properties, the following results are produced:

(1) Through bending test of pineapple leaf fiber, the following values of root and middle part of fiber are obtained: \( E_B \) (6.43GPa), \( R_B \) (294.59E-5cN·cm²), \( E_B \) (2.82GPa), and \( R_B \) (118.17E-5cN·cm²);
the resistance to bending of fiber root is stronger than that of middle part of fiber, which is related to the morphological structure of fiber; the fineness and density of root are higher than that of middle part; high fineness and density means large thickness of fiber, less internal air void, and higher degree of density inside fiber.

(2) As far as textile materials, the value of \(E_E\) (4.63GPa) of pineapple leaf fiber is larger than that of ramie (\(E_E\) (3.83GPa)) and of woolen (\(E_E\) (1.36GPa)); the value of \(R_R\) (206.38E-5cN·cm²) of pineapple leaf fiber is much larger than that of ramie (\(R_R\) (1.05E-5cN·cm²)) and of woolen (\(R_R\) (0.04E-5cN·cm²)). In terms of physical property of bending, it is more difficult to bend and spin chiffonelle with pineapple leaf fiber than with ramie and woolen, and is more liable to cause skin irritation. Therefore, pineapple leaf fiber can be used for making textile products only after being further processing such as degumming and refinement.

(3) The compression-restoration curve of pineapple leaf fiber root is in a shape similar to that of middle assembly, monotonic notching. This indicates that pineapple leaf fiber root is similar to middle assembly in respect of compression restorability. The compression curve doesn’t coincide with the restoration curve, because fibers are of elasticity and viscosity concurrently.

(4) Mean \(R_c\) (57.73\%) of pineapple leaf fiber root is less than that (62.20\%) of middle fiber, \(L_e\) (0.46) of fiber root is larger than that (\(L_e\),0.43) of middle fiber, indicating that middle pineapple leaf fiber is easier to be compressed than root. Besides, \(R_c\) value is in positive correlation with compression recoverability. Pineapple leaf fiber is suitable to be used as filling material for thermal insulation.

Acknowledgements
This work was financially supported by the Hainan Natural Science Foundation (No. 519QN302).

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