Softness Evaluation of Keratin Fibers Based on Single-Fiber Bending Test

Weidong Yu,[1,2] Yuqing Liu[1]

[1]*College of Textiles, Donghua University, Shanghai 200051, People's Republic of China*
[2]*College of Textiles and Materials, Wuhan University of Science and Engineering, Wuhan 430074, People's Republic of China*

Received 12 July 2005; accepted 29 November 2005
DOI 10.1002/app.23898
Published online in Wiley InterScience (www.interscience.wiley.com).

ABSTRACT: The evaluation of single-fiber softness by bending is an ingenious and vital approach for the basic investigation of both the fiber bending properties and the textile softness. The bending behavior and bending modulus of wool, alpaca and silk fibers have been measured by an axial-buckling method developed by the authors, which uses the fiber compression bending analyzer (FICBA). The bending properties of single fibers were quantified by calculating the equivalent bending modulus and the flexural rigidity by measuring the protruding length and diameter of fiber needles and the critical force, P_{cr}, obtained from the peak point of the force-displacement curve. The measured data showed that the equivalent bending modulus of the alpaca fiber is higher than that of wool fiber, and even the rigidity is 10 times as high as wool, but its friction coefficient is lower than that of wool, which means that the soft handle of alpaca fabrics is mainly due to the smooth surface and low friction coefficient of alpaca fibers in contrast to that of wool fiber. For the silk fiber, despite high equivalent bending modulus, the smoother handle of silk should be mainly due to the thin fiber diameter in contrast to that of keratin fibers. © 2006 Wiley Periodicals, Inc. J Appl Polym Sci 101: 701–707, 2006

Key words: wool; alpaca; softness; single-fiber bending; equivalent bending modulus

INTRODUCTION

Soft fabrics should have smooth surface, comfortable touch, and lower flexural rigidity.[1] The essential issue is referenced to two aspects, i.e., the flexibility of fibers themselves and the slippage capacity between fibers and yarns. The former is dependent on diameter, equivalent modulus, cross-sectional shape, and equivalent movable length of the fiber; the latter relies on fiber surface friction, surface morphology, crimp characteristics of fibers, and the lubricant on the fiber. Some early researches about keratin fiber softness were focused on fiber surface property, fiber assembling compression performance, and subjective evaluation of touching.[2–4] A recent publication[3] suggested that the results from the current methods on the resistance to compression test are not suitable for low-curvature fibers such as alpaca, and believed that fiber softness could be measured by pulling a fiber bundle passing a series of pins. Although it is an interesting and fruitful testing, it describes the effects of fiber stiffness, diameter, crimp, and smoothness together; so it is difficult to identify the main factors contributing to the soft feeling of alpaca fiber. Because of the lack of single-fiber bending techniques applicable to softness measurement, the study on fiber softness can stop only at the evaluation of fabric handle or fiber assembling compression. The development of an axial-compression–bending method for single fibers has been made,[4,5] so that the bending behavior of keratin fiber can be characterized directly.

Correspondence to: Y. Liu (liuyq@mail.dhu.edu.cn).

Journal of Applied Polymer Science, Vol. 101, 701–707 (2006)

THEORETICAL

Equivalent bending modulus of single fiber

For the complex fine structure of keratin fibers [Fig. 1(A)], the mechanical property is anisotropic. Suppose bending a fiber to an angle θ with a radius of curvature ρ as shown in Figure 1(B). The fibrils in outer side of bending, namely outer fibril layer, are extended, and those in inner side, namely inner fibril layer, are compressed, but a synaptic plane in the center, known as the neutral face "*NN*," will be unchanged in length. As a result of the extension and compression, stresses will be set up that give an internal couple to balance the applied couple *M*. Consider a fibril $\bar{ab}$ at a perpendicular distance y from the neutral plane, thus

$$\varepsilon_y = y/\rho \qquad (1)$$

$$\sigma_y = E_y \varepsilon_y \qquad (2)$$

where E_y is the tangent modulus and obtained from stress–strain (σ–ε_y) curve at y layer, as shown in Figure 1(D) theoretically. In fact, σ–ε_2, namely tensile stress-strain curve, is easily found by tensile testing, whereas σ–ε_1, pure compressing stress–strain curve, is difficult to achieve for flexible and fine fibers up to now. So we leave this problem and adapt a classical expression for the applied couple, M,

$$M = -\int_{A2} \sigma_{y2} y_2 dA_2 - \int_{A1} \sigma_{y1} y_1 dA_1 = -\int_{A} \sigma_y y dA$$

$$= -\frac{1}{\rho}\int_{A} E_y y^2 dA = E_B I Y'' \quad (3)$$

where $y'' \approx 1/\rho$, I is the moment of inertia, σ_{y1} and σ_{y2} are the fibril's compression stress and tensile stress, respectively, A_1 and A_2 are the fibril's compression area and tensile area, respectively, y_1 and y_2 are the compression fibrils and the tensile fibrils at distance from the neutral plane, respectively, σ_y is the fibril stress, A is the cross-sectional area, and E_B, the equivalent bending modulus, is an integral and average value of the tensile tangent modulus and compression modulus. So we avoid the analytical calculation of equivalent modulus from the tangent modulus, E_y.

If the tangent modulus, E_y, is divided into two parts, E_{y1} and E_{y2}, where E_{y1} and E_{y2} represent the compression and tensile tangent modulus at y layer, respectively, and assuming that E_{y1} and E_{y2} are constant and equal to E_1 and E_2, the equivalent bending modulus, E_B is

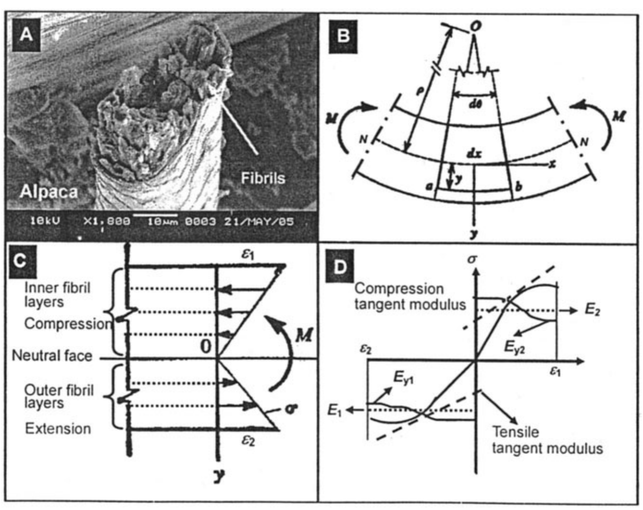

Figure 1 Fiber morphology and bending of single fiber. (A) Fibril structure of alpaca fiber. (B) Schematic of single-fiber bending. (C) Stress distribution of fibril layer during bending. (D) Tangent moduli of different fibril layers.

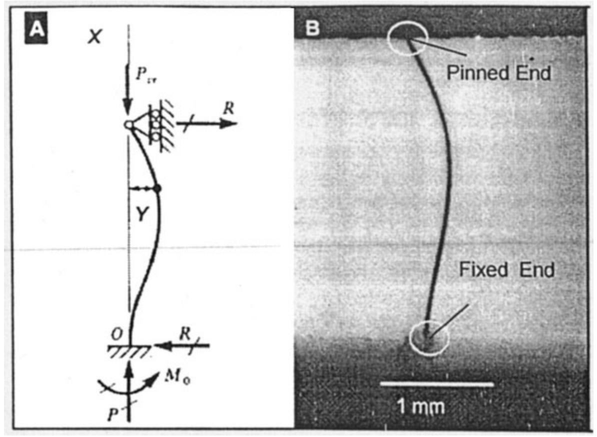

Figure 2 Axial-compression–bending of single fiber. (A) Schematics of the axial-compression–bending test. (B) Real image of bending and buckling of single alpaca fiber.

$$E_B = v_1 E_1 + v_2 E_2 \quad (4)$$

where v_1 and v_2 represent the volume fraction of a bent fiber according to its neutral face, and $v_1 + v_2 = 1$.

Because E_t depends on the layer of fibrils in a fiber, to ignore the structural effect, that is, ε_y, E_1 and E_2 are always equal to or smaller than Young's modulus or initial of tensile and/or compression modulus. As the mechanical properties of keratin fiber is different from isotropic metals, such as large and inelastic deformation, the equivalent bending modulus, E_B, should be much smaller than the initial modulus.

Although E_y can be estimated in theory with eq. (4) and the relevant assumptions, we adapt a new and measured method to evaluate the equivalent bending modulus of keratin fibers, because of the difficult or impossible determination of E_2, v_1, and v_2.

Axial-compression–bending of single fibers

Schematics of the axial-compression–bending test and the coordinate system used for the analysis are shown in Figure 2. A compression force, P_{cr}, is applied to the single fiber with length L. The critical force and buckled-mode shape for the single fiber is fixed at base and pinned at the top.[6] We solve the differential equation to find P_{cr}, according to the model as shown in Figure 2(A). When the fiber buckles, horizontal reactive forces, R, develop at the supports and a reactive couple M_0 develops at the base. The bending moment in the buckled fiber at distance X from the base is

$$M = PY - R(L - X) \quad (5)$$

From eqs. (4) and (5), the differential equation can be found as eq. (6)

$$E_B I Y'' = -PY + R(L - X) \quad (6)$$

So the general solution of the differential equation is

$$Y = C_1 \sin kX + C_2 \cos kX + R(L - X)/P \quad (7)$$

where a prime denotes differentiation of the displacement v with respect to the longitudinal coordinate X, $k^2 = P/EI$, L is the extruding length of fiber needle, P is the force in compressive axial, and R the horizontal reactive forces.

Three unknown constants C_1, C_2, and R can be solved through the three boundary conditions, $Y(0) = Y(L) = 0$ and $Y'(0) = 0$.

Let eq. (7) to match the three conditions to obtain $C_2 + RL/P = 0$, $C_1 k - R/P = 0$, $C_1 tgkL + C_2 = 0$

Nontriviality C_1, C_2, and R yields the following equation:

$$\begin{vmatrix} 0 & 1 & L/P \\ k & 0 & -1/P \\ tgkL & 1 & 0 \end{vmatrix} = 0$$

And obtain the buckling equation:

$$kL = tgkL \quad (8)$$

The smallest but nonzero value of kL that satisfies eq. (8) is $kL = 4.493$.

The corresponding critical force is

$$P_{cr} = (kL)^2 \frac{E_B I}{L^2} = \frac{20.19 E_B I}{L^2} \quad (9)$$

EXPERIMENTAL

Single-fiber axial-compression–bending test

The axial-compression–bending tests were carried out by using fiber compression bending analyzer (FICBA). (The FICBA was researched and developed by Textile Materials and Technology Lab in Donghua University,[5,7] and now manufactured by Powereach® Co., Shanghai.) An fiber was axially compressed between the mechanical stage and a loading piece under observation using an optical microscope,[8] as shown in Figure 2(B). To determine the relationship between the critical buckling force and the displacement for a single fiber, we assumed that one end of the fiber is fixed, but the other is pinned. So the base end of fiber was clamped by two-side-adhesive plaster, which was embedded in a metal groove to simulate the fixed end. And the top end of fiber was ground into the platen covered with sandpaper to avoid fiber tip slippage to simulate the pinned end. The axial compressive strength of single wool fibers was measured using a miniature loading apparatus where the fiber was compressed by moving a mechanical stage and the compressive force was directly detected with a load cell. The axial displacement was calculated from the loading time and the crosshead speed. The crosshead speed was 0.1 mm/s for the 2-mm long single wool fibers.

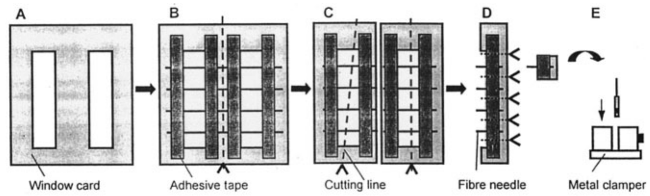

Figure 3 Overview of the approach used to prepare protruding single-fiber sample. (A) Every paper window is 5 mm wide and 25mm long. (B) Straightening the single fiber and stickling it to the paper window by glutinous resin, then covering it by adhesive tape. (C) Cutting the card into three independent paper windows and snipping the straightened fiber with different angles for suitable slenderness. (D) Scissoring the card to single-fiber sample. (E) Clamping the sample into the metal clamper.

Single-fiber sample preparation

The fibers, including Merino wool, Huacaya alpaca, and degummed silkworm silk, were collected for the single-fiber axial-compression–bending test. The fiber samples were extracted with ether and ethanol for clearing, then conditioned for more than 2 days under the standard temperature of 20 ± 2°C and relative humidity of (65 ± 2)%, and lastly, the three sorts of fibers were prepared into single-fiber needles. The preparing procedure is illustrated in Figure 3 in detail.

The single-fiber sample with certain protruding length was clamped by two metal grooves. The protruding length of single fiber is determined by fiber thickness. This means the single-fiber slenderness (length/thickness) should be appropriate, neither short enough to be compressed directly to yield, nor long enough to detect the miniature load of the critical force. The length and diameter of single-fiber sample are measured by an optical microscope with a CCD camera.

Diameter and slenderness of protruding fibers

The protruding length (L), diameter (D) and slenderness (L/D) are shown in Table I, with diameters used for the experiments. The protruding lengths of the merino wool, huacaya alpaca, and degummed silkworm silk fibers was directly measured by optical microscope with CCD camera on the FICBA. The diameter of single fiber was also measured by optical

TABLE I
Diameters and Slenderness of Single Fiber Sample

Sample	No	Diameter range (μm)	Mean diameter (μm)	Diameter standard deviousness (μm)	Slenderness range	Mean slenderness
Wool	20	18.6–42.1	28.1	7.0	18.1–43.9	30.7
Alpaca	36	23.9–58.6	45.1	9.1	23.7–56.3	36.6
Silk	15	8.4–12.3	10.7	1.2	39.4–80.2	60.3

method, but with different angles perpendicular to fiber, and then the mean diameter $\bar{D}$ and the range of fiber were obtained. The relationship between $\bar{D}$ and L for the wool, alpaca, and silk fibers are shown in Figure 4(A). The average slenderness $\overline{L/D}$ has been calculated from each L/D of the fibers. The relationships between L/D and D for each kind of fibers are illustrated in Figure 4(B). The dashed line stands for the mean diameter and mean slenderness. Although the mean diameter of wool $\overline{D_w}$ (28.1 μm) is smaller than that of alpaca $\overline{D_w}$ (45.1 μm), to make the result of bending test be more comparable, the protruding length has been adjusted through snipping the single-fiber sample shorter to let the mean slenderness of wool $\overline{(L/D)}_w$ (30.7) close to that of alpaca $\overline{(L/D)}_a$ (36.6).

RESULTS AND DISCUSSION

Force–displacement curves of axial-compression–bending

The typical plot of the force–displacement (F–d) data recorded in a single-fiber bending is shown in Figure 5. It can be seen that the critical force represents the maximum force carrying capacity of the signle fiber. As textile fibers have a lower proportional limit than metal fibers, when the stresses in outer fibrils exceed the proportional limit, the textile fiber no longer follows Hooke's law. Of course, the slope of the F–d curve is unchanged up to the level of force at which the proportional limit is reached. Then the curve continues upward, reaches a maximum, the critical force, P_{cr}. After that point, the stresses in outer layer result in the yield of the fibrils, and the curve turns downward. The detailed shapes of F–d curves depend upon the material bending properties and the fiber slenderness.

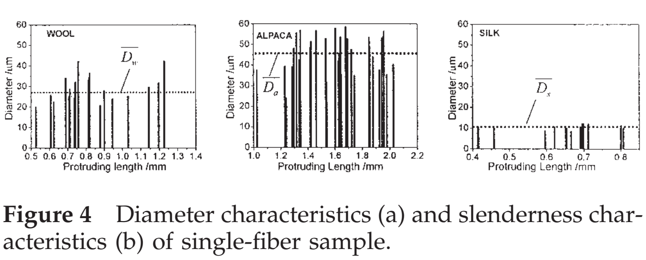

Figure 4 Diameter characteristics (a) and slenderness characteristics (b) of single-fiber sample.

The compression–bending curve during unloading does not follow the compression–bending curve during loading, and a hysteresis loop is produced. The possible explanation for this behavior is the internal friction between the fibrils and the molecular chains. These F–d curves illustrate two important characteristics. First, the critical force of the alpaca fiber with 42.6 μm diameter and 1.72 mm protruding length is the highest of the three single fibers with same slenderness, as shown in Table II. Second, the similar figure of F–d curves and the hysteresis loops, as shown in Figure 5, is due to the similar structure with relatively same slenderness.

Calculation of the equivalent bending modulus

The flexural rigidity of the single fibers, namely the resistance to bending, represents the softness or stiffness of the fibers.[9] Two factors work on it, one is fiber bending denoted by equivalent bending modulus, and the other is cross section denoted by diameter and

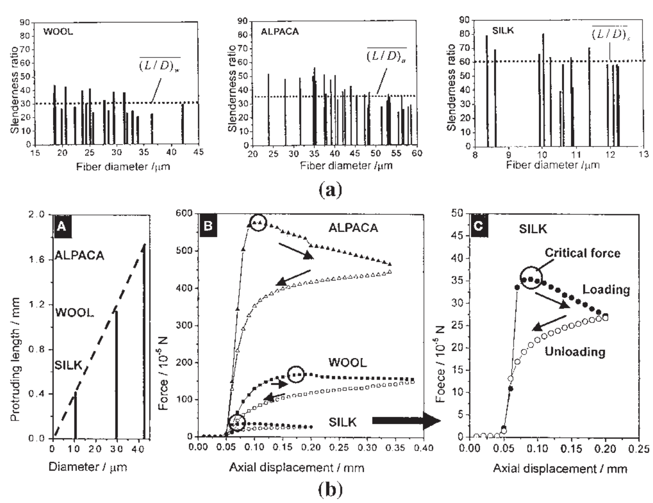

Figure 5 (A) The diameter and protruding length of three single-fibers. The fibers have similar slenderness for data comparing. (B) The F–d curves of axial-compression–bending test on the fibers. (C) The magnified F–d curve of single silk fiber. Loading and unloading processes of axial-compression–bending test are shown. The critical force can be measured on the F–d curve.

TABLE II
Diameters and Slenderness of Single Fiber Sample

Sample	Diameter (μm)	Protruding length (mm)	Slenderness	Critical force (10^{-5}N)
Alpaca	42.6	1.72	40.5	575.68
Wool	29.5	1.14	38.7	168.56
Silk	10.5	0.41	39.4	35.42

shape factor. To compare the bending properties of different kinds of fibers, the equivalent bending modulus must be calculated. Because the cross sections of some fibers are not exact circles, the fibers will usually bend at the thinnest part and easiest direction. The shape factor K_B is the ratio of the moment of inertia for a given cross-sectional area. So we can easily prove that the shape factor of equilateral triangle is bigger than that of ellipse:

$$I_{\text{circle}} : I_{\text{equilateral triangle}} : I_{\text{ellipse}} = \frac{1}{4\pi} : \frac{\sqrt{3}}{18} : \frac{1}{4\pi e} \quad (10)$$

where e is the ratio of the major axis to minor axis in ellipse. So the shape factor of equilateral triangle is 1.209, the shape factor of ellipse is $1/e$.

The shape factor according to different cross-sectional shapes has been adapted. Equation (9) can be expressed as eq. (11) considering the effect of shape factor, K_B.[5]

$$P_{\text{cr}} = \frac{20.19 E_B K_B I_0}{L^2} = \frac{20.19 \pi r^4 E_B K_B}{4L^2} = (0.99 E_B K_B)\frac{D^4}{L^2} \quad (11)$$

where E_B is the equivalent bending modulus, K_B represents shape factor (where the K_B of wool and alpaca is ~1 and that of silk fiber is 1.209), I_0 is the moment of inertia of the circle. Hence, the stiffness of the fiber needles depends on the value of E_B or D or L.

According to eq. (11), the critical force P_{cr} is directly proportional to D^4/L^2. Experimental data are shown in Figure 6. With linear regression and variance analysis, the regressive equation for wool fibers is $P_{\text{cr}} = (1.4502 \times 10^8)D^4/L^2$, and the coefficient of correlation $R = 0.849$.

The critical force can be simplified as:

$$P_{\text{cr}} = s\frac{D^4}{L^2} \quad (12)$$

Thus, the equivalent bending modulus is

$$E_B = \frac{1.01 \times 10^{-8} s}{K_B} \quad (13)$$

Here, s is the slope of the regression line and is equal to 1.4502×10^8, because the cross section of wool is nearly a circle, $K_B = 1$. The cross section of alpaca is nearly an ellipse, with the ratio of the major axis to minor axis e about 4/3, and $K_B = 0.75$; The cross section of silk is nearly an equilateral triangle, $K_B = 1.21$. Thus, the equivalent bending modulus of the single wool fiber is 1.47 GPa; the flexural rigidity is 4.46×10^{-5} cN cm^2. The results of calculation are shown in Table III.

The essential characteristic value of fiber bending and buckling is reflected by the equivalent bending modulus, which is independent of fiber diameter and determined only by fiber structure. The integral average sum of the tensile tangent modulus and compression modulus, according to eq. (4), is numerically equal to the equivalent bending modulus. From all of our measurements, the equivalent bending modulus of alpaca is larger than wool to certain extent, and three times smaller than that of silk, which suggests that the bending properties of keratin fibers is relatively similar, but different with silk protein fibers. The reason is probably due to the difference of α-helical and β-sheet structures.

The flexural rigidity, $E_B I$, is the product of equivalent bending modulus E_B and moment of inertia I. The moment of inertia is determined by fiber diameter and cross-section shape. So the softness or stiffness of single fibers should combine the equivalent bending modulus with fiber diameter or cross-section shape.

A comparison of bending characteristics of alpaca and wool (see Table III) shows that the equivalent bending moduli are near, but the flexural rigidity of alpaca is 10 times greater than that of wool, which is caused by the fiber diameter. Although the result indicates that the single alpaca fiber is stiffn, the yarn and fabric made of alpaca fibers, however, are still

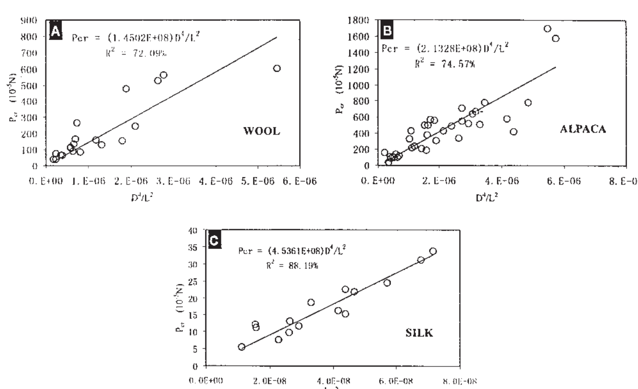

Figure 6 The relationship of critical force with D^4/L^2. (A) Wool fibers, (B) alpaca fibers, and (C) silk fibers.

TABLE III
Bending Characteristics of Single Fiber Sample

Sample	No	Diameter mean (μm)	Diameter standard deviousness (μm)	Equivalent bending modulus (GPa)	Flexural rigidity (10^{-5}c N cm^2)
Wool	20	28.1	7.2	1.47	4.46
Alpaca	36	45.1	9.1	2.15	43.55
Silk	15	10.7	1.2	4.58	0.29

with a softer handle that is attributed to the smooth surface characteristic of alpaca fibers.

Fiber friction

The frictional interaction between fibers is determined by the morphology of fiber contacting surfaces and the adherent forces between them. Figure 7 shows the SEM images of a typical alpaca fiber and a wool fiber. Compared with the wool fiber, the alpaca fiber scales are thinner and denser. The lower scale height and higher scale frequency for alpaca fibers make the fiber slip easier than wool fibers do.

Friction coefficient, μ, measured by the capstan roller method for frictional tests of single fiber are used to compare the friction characteristic of wool, alpaca, and silk. The friction coefficient can be calculated from the formula[10]:

$$\mu = \frac{InT_2 - InT_1}{\theta} \qquad (14)$$

where μ is the coefficient of friction; T_2 and T_1 are the leaving and incoming tensions, respectively; θ is the wrapping angle and equal to π. In the test, the running surface speed of the roller is 7.5 m/min. The roller is a hard steel roller.

The softness of yarns and fabrics handle is the combination of the effect of fiber surface friction characteristic and fiber bending properties. The frictional force varies with many factors such as load, real contact area, and geometry of contact. The structures of yarn and fabric are also attributed to the handle performance indirectly through changing the real contact area and interaction force between fibers. The coefficient of kinetic friction of alpaca fiber either with scales or against scale is less than wool fiber, as illustrated in Table IV. However, the equivalent bending modulus of alpaca fibers is greater than that of wool fibers. These results indicate that the soft handle of alpaca fabrics should be mainly due to the surface properties of alpaca fibers in contrast to wool fibers. As the silk has similar coefficient of kinetic friction as the alpaca, the smooth handle of the silk fabrics should be mainly due to the fiber diameter in contrast to keratin fiber.

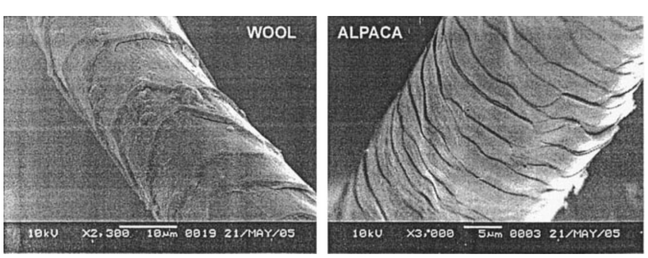

Figure 7 Scale structure of wool and alpaca.

CONCLUSIONS

Bending, flexibility, and buckling are very important mechanical properties not only for textiles but also for fibers. Using the FICBA, the bending properties of single fibers are quantified by calculating the equivalent bending modulus and the flexural rigidity by measuring the protruding length and diameter of fiber needles and the critical force P_{cr} from the F–d curves. The equivalent bending modulus of alpaca fiber (2.15 Gpa) is a little more than that of wool fiber (1.47 Gpa), whereas the flexural rigidity of alpaca fiber (43.55×10^{-5}cN cm^2) is 10 times as that of wool fiber (4.46×10^{-5}cN cm^2), which is due to the alpaca fiber diameter (45.05 μm). The experimental results indicate that the soft handle of alpaca fabrics should be due mainly to the smooth surface and low friction coefficient of alpaca fibers (0.279) in contrast to the high friction coefficient of wool fiber (0.312). As the silk has similar coefficient of friction (0.255) as that of the alpaca fibers and higher equivalent bending modulus (4.58 GPa) than that of keratin, the soft handle of silk should be due to the fiber diameter (10.67 μm) in contrast to

TABLE IV
Kinetic Friction of Single Fiber

Sample	Values of μ
Wool with scales	0.312
Wool against scale	0.352
Alpaca with scales	0.243
Alpaca against scales	0.279
Silk	0.255

keratin fibers (wool 28.1 μm; alpaca 45.1 μm). The results of single-fiber bending test verify that the method is useful, and provides a basis for researchers to investigate the softness of textile handle in single fiber. It can be believed that by using this measurement technique as a criteria test, to evaluate and characterize the bending properties of single fibers quantificationally can be realized.

The authors thank Dr. Lijing Wang for assistance with the fiber sample and Prof. Xugai Wang for helpful conversations.

REFERENCES

1. Aliouche, D.; Viallier, P. Text Res J 2000, 70, 939.
2. Roberts, N. F. Text Res J 1956, 26, 687.
3. Liu, X.; Wang, L. J. Text Res J 2004, 74, 535.
4. Liu, Y. Q.; Han, L.; Yu, W. D. J Donghua Univ 2004, 21, 143.
5. Yu, W. D.; Liu, Y. Q.; Han, L. Chin. Pat. 200310109512.3 (2003).
6. Popov, E. P.; Nagarajan, S.; Lu, Z. U. Mechanics of Materials; Prentice Hall: New Jersey, 1978; Chapter 13.
7. Liu, Y. Q. M.Sc. Dissertation, Donghua University, 2004.
8. Vlattas, C.; Galiotis, C. Polymer 1991, 32, 1788.
9. Hamburger, W. J. Text Res J 1948, 15, 295.
10. Morton, W. E.; Hearle, J. W. S. Physical Properties of Textile Fibers.The Textile Institute: Manchester, 1993, p 611.