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Study on the Effects of Single Fiber Tensile Properties on Bundle Tensile Properties through Estimation of HVI Bundle Modulus and Toughness

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Abstract: The HVI properties and Mantis® single fiber tensile properties were analyzed to evaluate the relationship between fiber and bundle tensile properties For this study, a new method has been developed for estimating the modulus and toughness of cotton fiber bundles directly from the HVI tenacity-elongation curves The single fiber tensile properties were shown to be translated well into the bundle tensile properties. The single fiber breaking elongation was found to be the most significant contributing factor to bundle tensile properties. The bundle breaking elongation and toughness were shown to increase as the single fiber breaking elongation increased. The bundle modulus increased as the single fiber breaking elongation and/or standard deviation of single fiber breaking elongation decreased.

Keywords: Bundle Modulus, Bundle toughness, HVI, Mantis®

Introduction

Beginning in 1993, all U.S. cotton crops have been classed by the HVI(high volume instrument). Instead of single fibers, fiber bundles are measured on the HVI system. The tensile properties of HVI bundle are largely determined by the tensile properties of the component fibers within the bundle. Therefore, a proper interpretation and utilization of bundle tenacity-elongation curves require a basic understanding on the relationship between bundle tensile properties and the tensile properties of the fibers making up the bundle. In order to accomplish this, a large amount of single fiber tests need to be performed. In the early 1980s, a rapid, semiautomatic, single fiber tester, called Mantis® was developed by Schaffner Technologies and later modified by Zellweger Uster Inc. The Mantis® tester is capable of testing about three fibers per minute. It captures more than 1000 load-extension values for each fiber, as it is broken. The data are automatically stored in a computer for various analyses.

In an effort to increase the utility of HVI tests, "bundle modulus" and "bundle toughness" were estimated from the HVI tenacity-elongation curve. The ultimate objective is to apply them to fiber selection, bale laydown and prediction of spun yarn strengths.

Experiments

We obtained 50-pound cotton samples for each of six varieties, two varieties each for three categories from Plains Cotton Cooperative Association (PCCA). The first category consists of two varieties with different HVI fiber length ("C11", "C12"), the second with two different HVI length and micronaire ("C21", "C22"), and the third with two different HVI tenacity and micronaire ("C31", "C32"). Each 50-pound cotton sample was formed by pulling roughly 16~17 pounds of cotton from each of three bales randomly selected.

These cottons were tested for their single fiber and bundle tensile properties using Motion Control (MCI) HVI[1] and Mantis®[2] after 24 hrs conditioning in a standard atmosphere laboratory (70±2 °F, 65± 2% R.H.). Based on the fiber data, the relationship between single fiber and bundle tensile properties was investigated.

Experimental Study on Single Fiber Testing

A large amount of data on tensile properties of single fibers has been acquired through Mantis® testing. The single fiber tensile properties include strength, elongation, modulus (K), work and crimp. The modulus is defined as the ratio of breaking strength to breaking elongation. The work is defined as the total area under the load-elongation curve. The crimp is defined as the difference between the fiber curvilinear length between the clamps and the gauge length expressed in percent of the latter.

A total of 10,800 single fiber tests on six cottons, i.e., 1,800 tests on each cotton, or 600 tests on each bale, were performed. The single fiber tensile properties are averaged by bale and then by variety. Therefore, the statistics for C11 mean average statistics for C11A, C11B, and C11C. The statistics for the six varieties are given in Table 1.

Experimental Study on HVI Tensile Properties

A total of 90 HVI tests were performed, 5 beards for each of the 3 bales of 6 varieties, for the PCCA cottons to obtain the bundle tenacity-elongation curves using MCI HVI. The bundle tenacity means specific stress and the bundle elongation means tensile strain in percentage. The summary statistics are given in Table 2.

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Table 1. Mantis® single fiber tensile properties of PCCA cottons

Cotton Type		Strength (gf)	Elon. (%)	K (gf)	Work (μJ)	Crimp (%)
C11	Avg.	5.64	15.57	0.397	14.107	2.19
	S.D.	2.55	5.96	0.211	8.110	1.96
C12	Avg.	6.01	13.40	0.514	12.903	2.23
	S.D.	2.76	5.27	0.660	7.390	1.83
C21	Avg.	5.81	12.85	0.498	11.700	2.22
	S.D.	2.42	4.61	0.256	5.970	1.86
C22	Avg.	6.72	12.92	0.553	13.950	2.45
	S.D.	2.94	4.98	0.540	8.077	2.26
C31	Avg.	4.91	15.49	0.352	12.470	2.41
	S.D.	2.39	6.18	0.203	7.717	1.88
C32	Avg.	4.39	12.67	0.386	9.290	2.50
	S.D.	2.12	4.73	0.484	5.937	1.92

Table 2. HVI properties of PCCA cotton

Cotton Type		Tenacity (gf/tex)	Elongation (%)	Modulus (gf/tex)	Toughness (gf/tex)
C11	Average	32.79	7.37	32.88	41.86
	S.D.	1.63	0.59	5.03	3.07
C12	Average	32.69	6.37	41.92	32.11
	S.D.	1.89	0.45	3.41	3.51
C21	Average	32.14	6.09	43.54	28.83
	S.D.	1.21	0.40	4.81	1.92
C22	Average	33.83	5.97	46.72	30.34
	S.D.	1.47	0.32	3.53	1.99
C31	Average	30.11	7.29	30.57	36.84
	S.D.	1.91	0.46	3.84	3.08
C32	Average	27.27	6.22	36.13	23.96
	S.D.	1.76	0.53	3.04	3.07

In order to gain a better understanding on the relationship between the tensile properties of a bundle and that of its constituent fibers, the "bundle modulus" and "bundle toughness" were obtained from bundle tenacity-elongation curves. The latter is defined as the total area under the tenacity-elongation curve.

Estimation of Bundle Modulus and Toughness from HVI Tenacity-Elongation Curves

The actual load during the HVI bundle break was estimated by the relationship between the voltage output of the force transducer and the load acting on the transducer. The bundle size was obtained by a direct weighing method. First, the position along a beard where the HVI broke the beard was determined. Then an 1/8-inch segment of the beard was cut off at the position by use of a cutting device, and the fibers were weighed on a high precision electronic balance. According to the actual breaking load and actual bundle size, the tenacity (gf/tex) of a bundle was estimated. The actual HVI bundle breaking elongations were also obtained through the relationship between the voltage output of the displacement transducer and the actual displacements. A tenacity-elongation curve of "C11A" cotton from HVI is given in Figure 1 without smoothing.

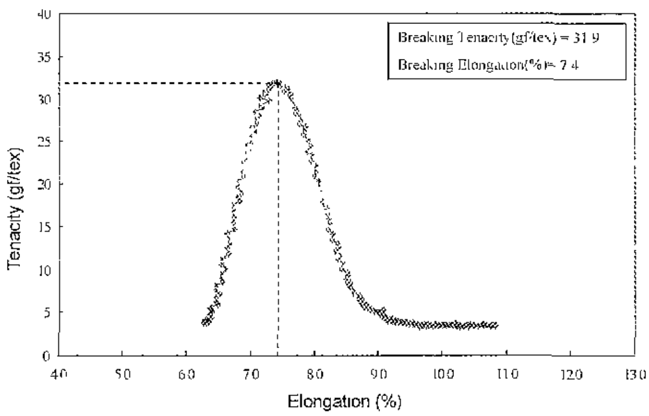

Figure 1. HVI bundle tenacity-elongation curve before smoothing (C11A).

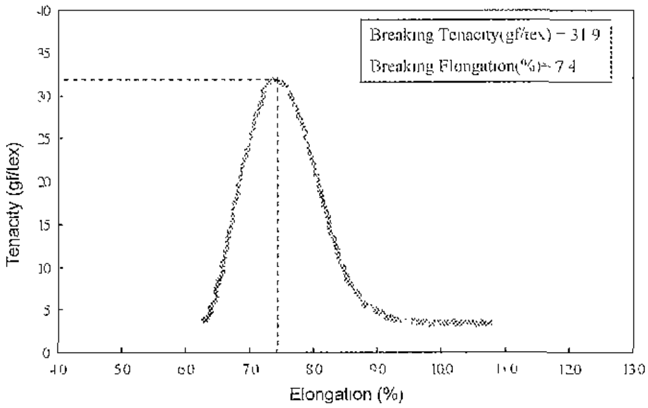

Figure 2. HVI bundle tenacity-elongation curve after smoothing (C11A).

While an HVI is supposed to measure the load using CRE (constant rate of elongation) method, Figure 1 shows that the elongation does not increase monotonically with small local oscillations. This type of noise is quite common in highly sensitive force transducers, and is not easily removed without lowering sensitivity of the instrument. In order to hide the noise in the original curve, the tenacity and elongation values were smoothed using the Savitzky-Golay[3] method. Seven data points were considered at a time in the smoothing routine. Figure 2 shows the tenacity-elongation curve of "C11A" after smoothing.

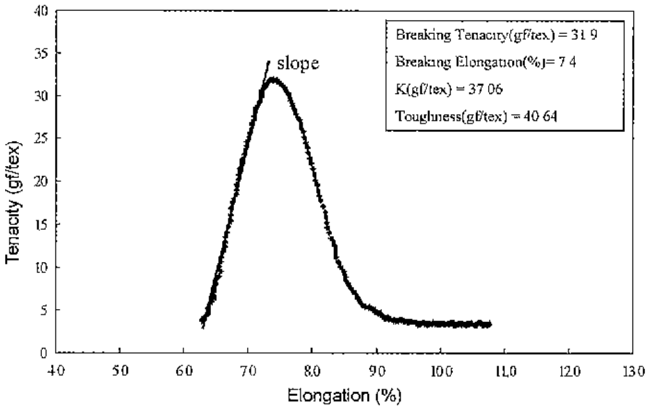

Figure 3. Modulus of HVI tenacity-elongation curve (C11A).

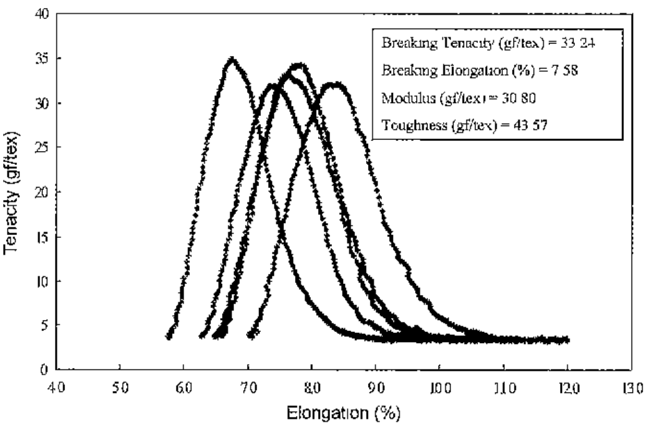

Figure 4. HVI tenacity-elongation curves before shifting (C11A).

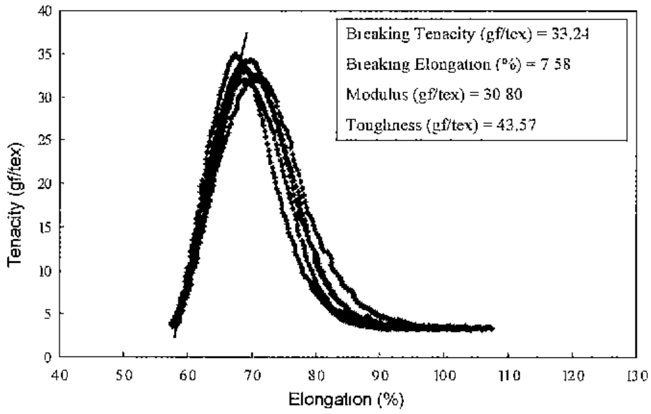

Figure 5. HVI tenacity-elongation curves after shifting (C11A).

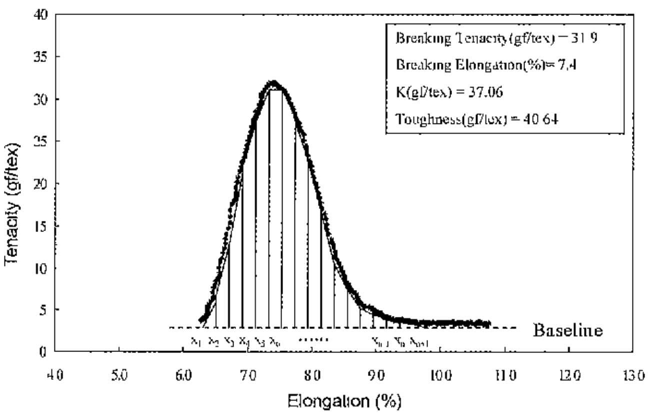

Figure 6. Toughness of HVI tenacity-elongation curve (C11A).

Modulus of HVI Tenacity-Elongation Curve

The "bundle modulus" was obtained from the bundle tenacity-elongation curve by measuring the rising slope of the load. The slope was obtained by calculating the ratio of two x-y coordinates from the bundle tenacity-elongation curve, as shown in Figure 3. The (x_1, y_1) is the deflection point on the left portion of the tenacity-elongation curve where the slope begins to stabilize following the removal of fiber crimps and (x_2, y_2) is the point where the slope begins to decrease significantly. Then, the bundle modulus(gf/tex) is computed as $y_2 - y_1 / x_2 - x_1$. Figure 3 shows the bundle tenacity-elongation curve with bundle modulus.

In order to compare the shape of the five tenacity-elongation curves and draw the average modulus line, all tenacity-elongation curves were shifted and aligned to the one with smallest elongation value. The tenacity-elongation curves before shifting are given in Figure 4. The tenacity-elongation curves thus obtained with average modulus lines are given in Figure 5. It can be seen from the figures that the shape of HVI tenacity-elongation curves are similar within a cotton sample. The moduli obtained from the tenacity-elongation curves are given in Table 2.

Toughness of HVI Tenacity-Elongation Curve

The toughness of a bundle was obtained by numerical integration method using the trapezoidal rule[4]. It represents the entire area under the tenacity-elongation curve, $f(x)$. To evaluate $\int_a^b f(x)dx$, the interval from a to b was subdivided into n subintervals, as shown in Figure 6. The area under the curve in each subinterval is approximated by the trapezoid formed by replacing the curve by its secant line drawn between the endpoints of the curve. The integral is then approximated by sum of all the trapezoidal areas. While there is no need to make the subintervals equal in width, the formula becomes simpler by doing so. By letting h be the constant interval width Δx, the area of a trapezoid is obtained by multiplying its average height to the base width of each subinterval as

$$\int_{x_i}^{x_{i+1}} f(x)dx \cong \frac{f(x_i) + f(x_{i+1})}{2}(\Delta x) = \frac{h}{2}(f_i + f_{i+1}) \qquad (1)$$

For the entire interval, therefore, the $[a, b]$, n subintervals of size h yield the result

Table 3. Correlation coefficients between single fiber and bundle tensile properties

Single Fiber Tensile Properties vs. Bundle Tensile Properties	Correlation Coefficients(ρ)	p-value
Single Fiber Breaking Strength vs. Bundle Breaking Tenacity	0.864	0.0001
Single Fiber Breaking Elongation vs. Bundle Breaking Elongation	0.839	0.0001
Single Fiber Modulus vs. Bundle Modulus	0.819	0.0001
Single Fiber Work-to-Break vs. Bundle Toughness	0.669	0.0024
Single Fiber Modulus vs. Bundle Breaking Tenacity	0.600	0.008
Single Fiber Work-to-Break vs. Bundle Breaking Tenacity	0.831	0.0001
Single Fiber Breaking Elongation vs. Bundle Toughness	0.880	0.0001
Single Fiber Breaking Elongation vs. Bundle Modulus	−0.652	0.0034
S.D. of Single Fiber Breaking Elongation vs. Bundle Modulus	−0.668	0.0025

$$\int_a^b f(x)dx \cong \sum_{i=1}^{n} \frac{h}{2}(f_i + f_{i+1}) = \frac{h}{2}(f_1 + 2f_2 + 2f_3 + \ldots + 2f_n + f_{n+1}) \quad (2)$$

The toughness thus obtained from the tenacity-elongation curves are given in Table 2.

Statistical Analyses on Single Fiber and Bundle Tensile Properties

The relationship between single fiber and bundle properties was investigated to calculate the correlation coefficients (ρ) between the fiber and bundle properties.

Correlation analyses were run using SAS® system in order to evaluate the relationship between the single fiber and bundle properties. The fiber and bundle properties were averaged by bale and by variety in providing the summaries. The correlation coefficients obtained between single fiber and bundle tensile properties were all highly significant (p-value<0.01) as shown in Table 3. The p-value[5] means that the smaller p-value, the stronger the sample evidence that alternative hypothesis ($\rho \neq 0$) is true. Clearly, the single fiber tensile properties are directly translated into bundle tensile properties. The bundle breaking tenacities show highly significant correlations with single fiber moduli and work-to-break.

It can been seen from Table 3 that the most significant single fiber tensile property which determines the bundle tensile properties is the single fiber breaking elongation. The bundle breaking elongation and toughness are shown to be increasing as the single fiber breaking elongation increases. The bundle modulus is also shown to increase as the single fiber breaking elongation and standard deviation of single fiber breaking elongation decrease.

Conclusions

1. The "bundle modulus" and "bundle toughness" of cotton fibers were estimated from HVI tenacity-elongation curves in order to gain a better understanding on the relationship between the tensile properties of a bundle and those of its constituent fibers.
2. The single fiber tensile properties were found to be translated well into the bundle tensile properties. The single fiber modulus and work-to-break showed highly significant correlations with the bundle breaking tenacity.
3. The single fiber breaking elongation is found to be the most significant contributing factor to the bundle tensile properties. The bundle breaking elongation and toughness are shown to increase as the single fiber breaking elongation increases. The bundle modulus increases as the single fiber breaking elongation and/or standard deviation of single fiber breaking elongation decrease.

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