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QUALITY MEASUREMENTS

Relating Bundle Strength to Mantis Single Fiber Strength Measurements

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INTERPRETIVE SUMMARY

One of the major goals of the cotton producer is to supply raw fibrous material that is consistently strong enough to compete with other natural and synthetic textile fibers for use in the manufacturing of quality goods. The goal of this research is to examine the relationship between the physical makeup and structure of cotton fibers and their ultimate strength or performance. The approach measured the strength of fibers, both individually and in parallel bundles, in various ways. An evaluation was carried out on a new, single fiber tensile tester called the Mantis[1] to determine how its results could be made compatible with conventional bundle strength testers. The most significant result from this work is that the bundle strength of cotton, and thus ultimately its potential for high performance, can be accurately predicted by knowledge of the force to break individual fibers and their electro-optically measured ribbon width as measured by Mantis. This discovery should greatly assist the fiber scientist in evaluating the overall quality of cotton.

ABSTRACT

Relationships between cotton (*Gossypium hirsutum* L.) fiber structure/morphology and strength have been examined for a wide range of physical and genetic properties. In particular, the relationships between the single fiber (Mantis) strength and various bundle strength measurements including stelometer and high volume instrument (HVI) were determined. In addition, relationships between single fiber strength and fiber physical/dimensional properties as obtained from the advanced fiber information system (AFIS) and image analysis were determined. Both the stelometer tenacity (T1, R^2 = 0.952) and HVI breaking strength (R^2 = 0.783) can be expressed by a multilinear relationship that includes the Mantis breaking load and projected fiber ribbon width. Both the stelometer tenacity (R^2 = 0.907) and HVI breaking strength (R^2 = 0.720) are linearly proportional to the ratio of the Mantis breaking load to the square of the projected ribbon width determined by the Mantis electro-optical sensor.

One of the major challenges for the cotton producer is to supply a raw material with consistent and uniform strength capable of competing with other natural and synthetic textile fibers for use in the manufacturing of quality goods. This requires continued research on cotton to improve fiber strength. A significant recent advance in the technology of fiber strength measurements has been the development of the Mantis single fiber tensile tester (Sasser et al., 1991). In a more recent study, Hebert et al. (1995) discussed the latest version of Mantis in which the hook over which the fiber is looped is replaced by a pair of clamps that grip the fiber ends. Also, significantly, an electro-optical system is included for measuring the projected ribbon width of each fiber prior to breaking. Mantis single fiber strength and elongation were reported to correlate well with single fiber strength and elongation measured on the Instron tensile tester. Similarly, ribbon width was

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[1] Trade names are necessary to report factually on available data. The USDA neither guarantees nor warrants the standard of the product or service, and the use of the name USDA implies no approval of the product or service to the exclusion of others that may be suitable.

Abbreviations: AFIS, advanced fiber information system; HVI, high volume instrument; T1, stelometer tenacity (gf/Tex); T(HVI), HVI bundle strength (gf/Tex); MIC, micronaire; Tb, Mantis breaking load (gf); RW, Mantis ribbon width (µm); AAF, cell wall area by AFIS (µm^2); PAF, fiber perimeter by AFIS (µm); AIA, cell wall area by image analysis (µm^2); PIA, fiber perimeter by image analysis (µm); CRYST, x-ray crystallinity index (%); and XRAY, x-ray orientation angle (deg).

related to fiber fineness; Mantis breaking strength decreased with increasing gauge length; and the convolution counts of cotton fibers were predicted by the electro-optical measure of light scattering.

This research was undertaken to better understand Mantis measurements of the breaking strength of single fibers. These results would then be interpreted in terms of other physical property measurements (including AFIS and image analysis) as well as bundle strength measurements. This approach should lead to an improved understanding of the relationships between fiber structure and performance, enabling cotton scientists to combine breeding, genetics, and cultural practices to produce cottons having superior strength.

The general approach followed in this research was to: (i) select cottons having a wide range of physical and genetic properties; (ii) conduct a series of experiments to determine the strength and physical/dimensional properties of these cottons; (iii) study the interrelationships among the single fiber and bundle strength measurements; and (iv) search for relationships between the different measures of strength and corresponding physical/dimensional properties.

MATERIALS AND METHODS

Samples included eight Egyptian cottons, seven American cottons (studied earlier at SRRC by N. El-Gawad and J. Hebert) and five genetically related Texas cottons supplied by John Gannaway. Results from the Texas cottons were first reported at the Beltwide Cotton Conferences (Faerber and Gannaway, 1995). The 20 cottons were chosen for their genetic diversity and had a wide variation in their fiber properties (especially in the areas of length, strength, and fineness).

The experimental procedures followed in this research are listed here.

Mantis. The procedures using single fiber tensile tester outlined by Hebert et al. (1995) were followed and included three repetitions of 150 single fiber breaks for each cotton. Parameters measured were the breaking load or force to break, Tb (g), and the fiber ribbon width, RW (µm).

Stelometer. A stelometer flat bundle tester was used to perform tests according to ASTM D- 1445-90 (ASTM, 1993a). Values were obtained for an average of four bundle breaks. The factors used in this research included the breaking tenacity, T1 (g/Tex).

High Volume Instrument. Rapid and automated measurements of fiber quality were made with HVI. Tests were performed according to ASTM D- 4605 - 86 (ASTM, 1993b). Data were obtained on a Spinlab 900 HVI system and included bundle breaking strength (g/Tex) and micronaire (MIC). Results are based on the testing of four beards per cotton.

Advanced Fiber Information System. Output from the fineness and maturity option of AFIS was used in this section as outlined in Bradow et al. (1996). The average of five replications of 5000 fibers each was calculated for each cotton. Measurements included average cell wall area, AAF (μm^2), and perimeter, PAF (µm), of the fiber samples.

Image Analysis. Procedures for sample embedding in a polymer matrix and sectioning are described by Boylston et al. (1993). Image analysis was carried out on a Cambridge Instruments Model 970 Image Analysis system equipped with a Chalnicon scanner that was interfaced to a Nikon Optiphot2-POL light microscope operating with a 20x objective lens in the transmission mode (Thibodeaux, 1996). Measurements of the individual fiber cross-sections included average cell wall area by image analysis, AIA (μm^2), and perimeter, PIA (µm), of the fiber samples. These data were based on a minimum of 1000 (single fiber) sections per sample.

X-Ray Diffraction. X-ray diffraction was used to measure the orientation of fibrillar crystallites about the fiber axis and degree of crystallinity of cellulose in the cotton. Rigaku Instruments Model DMaxB diffractometer equipped with a goniometer and special fiber bundle attachment was used. Procedures for measuring appropriate parameters on four replicates each of approximately 20 mg bundles of parallel fibers were followed using the method for measuring the orientation angle (XRAY) based upon Creeley et al. (1956) and for the degree of crystallinity or crystallinity index (CRYST) based on the method of Segal et al. (1959). Each bundle contains approximately 4000 fibers.

Our goal was to investigate the way in which Mantis breaking load (Tb) results could be combined with average fiber dimensional parameters determined by some of the established methods so as to correlate them with both the stelometer tenacity and the HVI bundle strength [T(HVI)]. It is well known that there is a poor relationship between Mantis breaking load (Tb) and bundle strength measurements, stelometer tenacity (T1), and the HVI bundle strength [T(HVI)]. The specific procedure used was forward step-wise linear correlation to develop a linear regression model. Linear combinations of Mantis breaking load (Tb) were considered with other physical properties associated with each cotton.

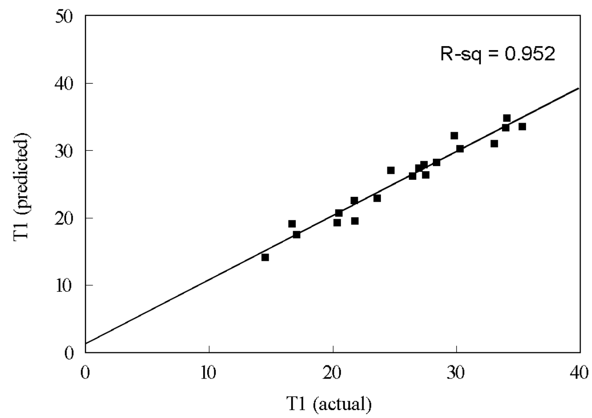

Fig. 1. Plot of the values of the stelometer tenacity (T1) for each cotton as predicted by linear combinations of Mantis breaking load (Tb) and fiber ribbon width (RW) from Eq. [1].

RESULTS AND DISCUSSION

In the first instance, stelometer tenacity (T1) is the dependent variable and trial independent variables include Mantis breaking load (Tb), Mantis ribbon width (RW), cell wall area by AFIS (AAF), cell wall area by image analysis (AIA), fiber perimeter by AFIS (PAF), fiber perimeter by image analysis (PIA), micronaire (MIC), x-ray crystallinity index (CRYST), and x-ray orientation angle (XRAY). Results of the correlation are given in Table 1. Initially, the single variable with the highest R^2 is PIA, the image analysis perimeter, with R^2 = 0.835. The next most significant is fiber ribbon width (RW) which adds R^2 = 0.045 to the model. The next step yields Mantis breaking load (Tb) with an additional partial R^2 = 0.071, with a cumulative R^2 of 0.952. The next step in the procedure shows that perimeter by image analysis (PIA) may be dropped from the model leaving the combination of Mantis breaking load (Tb) and fiber ribbon width (RW) accounting for a cumulative R^2 = 0.952. The excellence of this fit is depicted in Figure 1 which is a plot of the actual values of stelometer tenacity (T1) vs. the linear combinations of Mantis breaking load (Tb) and fiber ribbon width (RW) predicted from the following equation:

Table 1. Results of forward step-wise linear correlation model for T1, stelometer tenacity (gf/Tex) with several trial variables including Mantis breaking load (Tb), Mantis ribbon width (RW), cell wall area by AFIS (AAF), cell wall area by image analysis (AIA), fiber perimeter by AFIS (PAF), fiber perimeter by image analysis (PIA), micronaire (MIC), x-ray crystallinity index (CRYST), and x-ray orientation angle (XRAY).

Trial variable	Partial R^2	Model R^2	F	Prob>F
PIA	0.835	0.835	91.31	0.0001
Tb	0.045	0.881	7.101	0.0116
RW	0.071	0.952	36.293	0.0001
PIA (removed)	0.000	0.952	1.380	0.256

$$T1(predicted) = 62.28 + 2.66 * Tb - 3.95 * RW \quad [1]$$

Next, HVI bundle strength [T(HVI)] is the dependent variable and trial independent variables include Mantis breaking load (Tb), Mantis ribbon width (RW), cell wall area by AFIS (AAF), cell wall area by image analysis (AIA), fiber perimeter by AFIS (PAF), fiber perimeter by image analysis (PIA), micronaire (MIC), x-ray crystallinity index (CRYST), and x-ray orientation angle (XRAY). Results of the correlation are given in Table 2. The single variable with the highest R^2 is fiber ribbon width (RW) with R^2 = 0.471. The next most significant is Mantis breaking load (Tb) which adds an additional R^2 of 0.312 to the model with a resulting cumulative R^2 of 0.783. These results are depicted in Figure 2 where we plot the actual values of HVI bundle strength [T(HVI)] vs. the linear combinations of Mantis breaking load (Tb) and fiber ribbon width (RW) predicted from the following equation:

$$T(HVI)(predicted) = 58.18 + 2.454 * Tb - 3.158 * RW \quad [2]$$

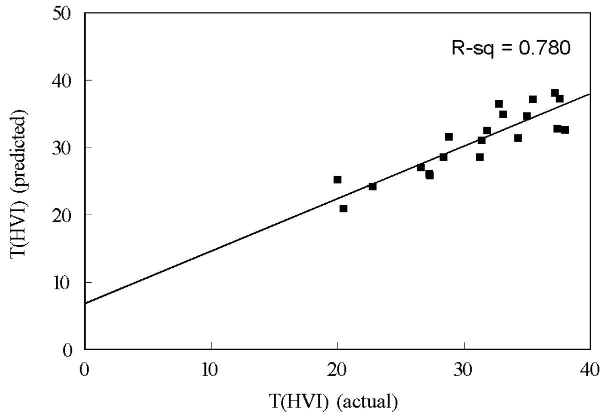

Fig. 2. Plot of the values of the high volume instrument (HVI) bundle strength T(HVI) for each cotton as predicted by linear combinations of Mantis breaking load (Tb) and fiber ribbon width (RW) from Eq. [2].

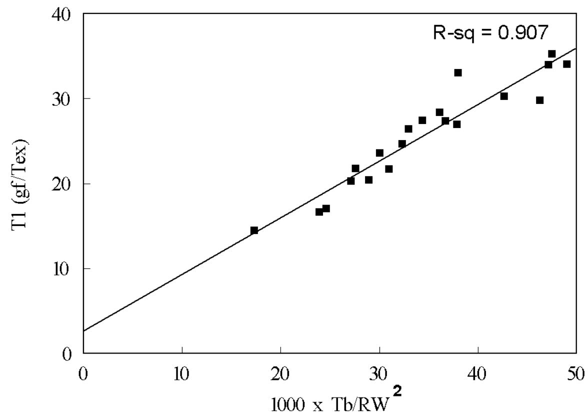

Fig. 3. Plot of the values of the stelometer tenacity (T1) for each cotton as a function of the ratio of the average Mantis breaking load to the square of the average fiber ribbon width [Tb/(RW)^2].

The final consideration is that both the stelometer tenacity (T1) and the HVI bundle strength [T(HVI)] parameters represent fiber tenacity or, in effect, breaking stress where the force to break the bundle is normalized or divided by the corresponding bundle mass or linear density as discussed earlier. This compensates for differences in fiber cross-sectional area, perimeter, or linear density. Thus, another (and more logical) way of using Mantis breaking load (Tb) to predict bundle tenacity is to normalize the breaking load to account for different single fiber cross-sectional, dimensional qualities. In fact, fiber cross-sectional area, perimeter, or linear density is not measured directly, but average values are obtained from AFIS, image analysis, and micronaire. Regression coefficients with several trial dimensional variables used as denominators for Mantis breaking load (Tb) are shown in Table 3. The trial variables consist of ratios of Mantis breaking load (Tb) to functions of several dimensional variables including image analysis wall area (AIA), AFIS wall area (AAF), image analysis perimeter (PIA), AFIS perimeter (PAF), fiber ribbon width (RW), and micronaire (MIC). Table 3 shows the values of R^2 and the corresponding levels of confidence (all data are significant at the 95% level or better). The highest correlation coefficient for the stelometer tenacity (T1) with a trial variable is obtained when using the ratio of the average Mantis breaking load to the square of the average fiber ribbon width [Tb/RW^2] which yields an R^2 of 0.907.

Similarly, the highest correlation coefficient for the HVI bundle strength [T(HVI)] is also obtained when using the ratio of the average Mantis breaking load to the square of the average fiber ribbon width

Table 2. Results of forward step-wise linear correlation model for T(HVI), HVI bundle strength (gf/Tex) with several trial variables including Mantis breaking load (Tb), Mantis ribbon width (RW), cell wall area by AFIS (AAF), cell wall area by image analysis (AIA), fiber perimeter by AFIS (PAF), fiber perimeter by image analysis (PIA), micronaire (MIC), x-ray crystallinity index (CRYST), and x-ray orientation angle (XRAY).

Variable	Partial R^2	Model R^2	F	Prob. >F
RW	0.6375	0.6375	31.66	0.0001
Tb	0.1422	0.7797	10.97	0.0041
PAF	0.0376	0.8174	3.29	0.0881*
AAF	0.0355	0.8529	3.62	0.0766*

*Not significant at the 95% level of confidence.

Table 3. Pearson correlation coefficients (r) relating fiber bundle strength parameters [stelometer tenacity (T1) and HVI strength, T(HVI)] to ratios of Mantis breaking load (Tb) to functions of several dimensional variables including image analysis wall area (AIA), AFIS wall area (AAF), image analysis perimeter (PIA), AFIS perimeter (PAF), fiber ribbon width (RW), and micronaire (MIC).

Trial variable	T1	T(HVI)
Tb/AAF	0.487	0.440
Tb/AIA	0.629	0.349
Tb/PAF	0.387	0.299
Tb/PIA	0.523	0.413
Tb/(PAF)^2	0.435	0.302
Tb/(PIA)^2	0.692	0.503
Tb/RW	0.690	0.582
Tb/(RW)^2	0.907	0.718
Tb/MIC	0.780	0.567

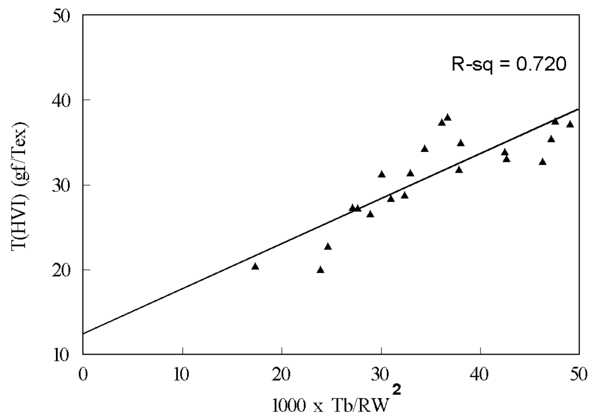

Fig. 4. Plot of the values of the high volume instrument (HVI) bundle strength T(HVI) for each cotton as a function of the ratio of the average Mantis breaking load to the square of the average fiber ribbon width $[Tb/(RW)^2]$.

$[Tb/RW^2]$ yielding an R^2 of 0.720. This relationship is illustrated in Figure 3. The trend line shown is given by the following equation:

$$T1 = 2.66 + 666 * Tb/(RW)^2 \qquad [3]$$

The agreement between HVI bundle strength [T(HVI)] and Mantis breaking load (Tb) for the cottons in this study is illustrated by the plot shown in Figure 4. There is some indication of increased scatter of the points off the trend line as compared with the data shown for stelometer tenacity (T1) in Figure 3. Note that the y-intercept (12.32 gf/Tex) is even larger than was obtained with T1. The equation of this line is given by the following:

$$T(HVI) = 12.32 + 530.49 * Tb/(RW)^2 \qquad [4]$$

After reviewing the results, it is clear that rather precise relationships exist between single fiber strength measurements (Mantis) and conventional bundle measurements (stelometer and HVI). In addition, measurements of fineness and maturity (by both AFIS and image analysis) are helpful in predicting fiber strength. One concern about the data is the significant offsets experienced in predicting stelometer and HVI bundle strengths. Our research in the future will center on three aspects:

a. obtaining similar data on additional cottons;
b. expanding our analysis to include considerations of Mantis fiber crimp and the time aligned array analysis; and
c. the inclusion of yarn performance data to check its predictability from these strength factors.

The following summarizes our findings from the studies of the 20 cottons:

1. Both the stelometer tenacity (T1) and HVI bundle strength [T(HVI)] can be expressed by a multilinear relationship that includes the Mantis breaking load (Tb) and the projected fiber ribbon width (RW).
2. Both the stelometer tenacity (T1) and HVI bundle strength [T(HVI)] are linearly proportional to the ratio of the average Mantis breaking load to the square of the average fiber ribbon width $[Tb/RW^2]$ where RW is determined by the Mantis electro-optical sensor.

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