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Using Fiber Elongation to Improve Genetic Screening in Cotton Breeding Programs

Abstract In this study, the bundle elongation and tenacity of cotton fibers were measured using a modified tensile testing instrument to which Pressley clamps (1/8" gage length) were adapted. 32 cotton genotypes with a range of bundle tenacity and elongation were carefully selected based on their distinct physical properties. The work of rupture was calculated from the load vs. elongation curves for each type of cotton. Results demonstrated the importance of fiber bundle elongation in the work of rupture of fiber bundles, which is critically important to processing performance. This study lays a foundation for future efforts to calibrate the high volume instrument elongation measurements and to breed new cultivars with improved work of rupture. This should result in lower fiber breakage when the cotton fibers are submitted to different mechanical stresses (ginning, carding, spinning, and weaving).

Key words tenacity, elongation, cotton, work of rupture

Cotton breeding programs must strive to deliver fibers that perform better in textile manufacturing [1-3]. This is critical for effective competition with the various man-made fibers and with international growths of cotton. Yet, several fiber properties not measured in the cotton breeding programs have a large impact on processing performance. Among these are the elongation characteristics associated with fiber tenacity. Backe [4] showed the importance of cotton fiber bundle elongation on yarn quality and weaving performances. The author concluded that cotton fiber bundle elongation should be measured and seriously considered when developing cotton lay-downs. He reported that the higher the cotton fiber bundle elongation, all other fiber properties remaining constant, the better the yarn's quality and resistance to the stresses and strains of weaving. Inheritance of cotton fiber tenacity has been studied extensively. May and Jividen [1] reported that "heritability of fiber tenacity is generally high for selection units ranging

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from single plants to population bulks." They reported that, among 18 studies undertaken between 1954 and 1994, the narrow sense heritability for fiber tenacity ranged from 0.10 to 0.86. The same authors reported that for fiber elongation the narrow sense heritability ranged from 0.36 to 0.90. May and Taylor [5] also reported negative correlations between fiber elongation and fiber tenacity.

In general, most of the breeders simply ignore fiber elongation because the lack of calibration procedures for high volume instrument (HVI) elongation makes it impossible to rely on such data. In addition, the literature produced by cotton breeders shows that even when elongation measurements are available (Stelometer tests) there is a lack of understanding of their meaning. Indeed, because of

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the negative correlation between elongation and tenacity, they often conclude that there is no need to work on elongation because it could result in lower tenacity. However, an exclusive focus on breaking strength (tenacity) is erroneous. The work of rupture is also important and the best way to improve it is to work simultaneously on tenacity and elongation.

The elongation characteristics associated with fiber tenacity are of critical importance at three junctures:

1. Ginning – the cleaning and removal of fibers from the seeds create stresses that break fibers which lack sufficient tenacity and elongation, resulting in elevated short fiber content (SFC).
2. Opening and Carding – these indispensable steps prior to spinning achieve the final cleaning of the fibers and arrange them into a continuous bundle of parallel fibers (called a sliver). Again, the SFC generated by these mechanical processes is negatively correlated with fiber tenacity and elongation.
3. Weaving – forming the spun yarns into a fabric on a weaving machine provides the ultimate test of yarn performance. Low levels of yarn breakage are required to achieve both the requisite weaving efficiency and fabric quality. Weaving has always been an abrasive and stressful process, but the speeds of modern weaving machines have magnified these problems.

The warp yarns are exposed to two major categories of stress: tension and dynamic fatigue. Tensions are of three types: the initial tension, the shed opening tension, and the beating-up tension. The “initial tension” refers to the equilibrium tension kept on the warp yarns being rolled off the yarn beam and fed through the weaving machine. The “shed” refers to the path traveled by the filling yarns through the warp yarns, formed by raising selected warp yarns. Actions at the shed are a major source of both tension and dynamic fatigue, caused by the very rapid opening-and-closing movements required to create the desired weaving patterns. (With a modern air-jet loom, the opening-and-closing time takes only about 20 ms, during which the yarns have to elongate more than 4% without breaking.) In addition, the warp yarns are simultaneously stressed by the acceleration of the filling yarn through the shed. The “beating-up” refers to the last operation of the loom in weaving, in which the last pick (filling yarn) inserted in the fabric is “beaten” into position against the preceding picks. All these actions generate abrasive tensions and dynamic fatigue. Given the demands made on yarns in weaving, it is clearly inadequate to rely on the traditional tenacity measurement to achieve desired performance levels. The measurement that is more appropriate for weaving performance is the work of rupture, because it captures the total energy required to break a bundle of fibers, which is a function of the combination of tenacity and elongation.

Meredith [6] reported on the amount of work required to rupture different textile fibers. The author reported that “the work of rupture is represented by the area enclosed by the stress-strain curve and the strain axis and would be half the product of breaking load and breaking extension if Hooke’s law were obeyed.” Meredith introduced a “work factor,” which was defined as the ratio of the actual work of rupture to the product of load and extension at break [6]. For a material obeying Hooke’s law, the “work factor” should be equal to 0.5. Meredith studied 15 international cottons. He reported that the “work factor” ranged from 0.45 to 0.49 (data obtained on individual cotton fibers). Therefore, we can consider that the work of rupture of individual cotton fibers complies with Hooke’s law. The major difference between our work and Meredith’s work is that we have determined the tensile properties on fiber bundles rather than single fibers. Thus, we are dealing with more complex systems where multiple fibers interact within the bundle.

Calibration of the HVI measurement for elongation is not available; therefore, measurements among HVI machines are not comparable. This project will validate the HVI measurement for elongation against the specially equipped tensile testing instrument, and evaluate ways to calibrate the HVI measurement.

Materials and Methods

Materials

Experiment 1

To demonstrate the association between tenacity and elongation, 547 samples from wild-type cotton genotypes and 567 cotton samples from various strain and cultivar performance trials grown in 2004 on the Texas High Plains were selected for comparison. The samples were tested on HVIs (HVI 900A, Uster, Knoxville, TN), with 10 replications for length, uniformity, elongation, and tenacity and four replications for micronaire. Tables 1 and 2 show a summary of the fiber properties from the two sample groups.

Experiment 2

To determine the relationship between tensile tests, 32 bales of cotton were selected based on their distinct physical properties. A representative sample of approximately 30 kg (70 lb) was taken from each bale. Each sample was homogenized according to the protocol used by the International Cotton Calibration Standard Committee (ICCS) [7] to produce reference cottons. From the card web produced, 10 samples were taken. The cotton samples were tested on HVIs (HVI 900A, Uster, Knoxville, TN), with 10 replications for length, uniformity, tenacity, and elongation

Table 1 Summary of the fiber properties of the selected 547 cottons.

	Micronaire	Length (in)	Uniformity (%)	Tenacity (cN/tex)	Elongation (%)
Maximum	6.5	1.45	87.90	38.3	13.70
Minimum	2.2	0.75	73.90	18.7	1.70
Average	4.0	1.04	82.82	27.0	6.94
CV%	19.8	10.67	2.53	9.7	31.95

Table 2 Summary of the fiber properties of the selected 567 cottons.

	Micronaire	Length (in)	Uniformity (%)	Tenacity (cN/tex)	Elongation (%)
Maximum	5.0	1.60	85.6	37.4	9.9
Minimum	2.4	0.95	77.8	22.8	3.2
Average	3.7	1.10	81.7	27.5	6.2
CV%	13.8	6.0	1.2	8.0	20.3

Table 3 Summary of the fiber properties of the selected 32 cottons.

	Micronaire	Length (in)	Uniformity (%)	Tenacity (cN/tex)	Elongation (%)
Maximum	5.0	1.20	83.5	33.5	7.6
Minimum	3.5	1.00	80.6	26.1	3.8
Average	4.4	1.10	82.2	29.4	5.4

measurements and four replications for micronaire measurements. They were also tested on the Advanced Fiber Information System (AFIS, Uster, Knoxville, TN), with five replications of 3000 fibers. Table 3 summarizes maximum, minimum, and average values of the physical properties of these samples.

Load–elongation determination

Bundle tenacity and elongation measurements were performed using a special device customized to accommodate Pressley clamps on a tensile testing instrument UT350 (The Testometric Company Ltd, U.K.). This attachment has been designed and manufactured at the International Textile Center at Texas Tech University (Figure 1). The sample preparation was performed according to the American Society for Testing and Materials (ASTM) Test Method D 1445-05 [8]. Force–elongation curves were obtained on the 32 cotton samples. During the course of this experiment two International Cotton Calibration Standard (ICCS) cotton standards were tested daily to track any possible drift; none was observed. The speed of the pulling clamp was set to 50 mm/min and 50 replications per sample were performed. We consider this method as being our reference. Therefore, we choose to perform 50 replications to obtain a high level of precision.

Work of rupture calculation

The work of rupture was calculated from the stress vs. strain, load/fiber vs. strain, and specific stress vs. strain curves by fitting the curves and calculating the area under the curves using the Table Curve software package (Table Curve 2D 5.0, SPSS, Chicago, IL). Details are given in the Results and Discussion section.

Experiment 3

To check the HVI's stability, we selected eight bales of upland cotton based on their HVI properties. Large samples were drawn from the bales without attempting to homogenize the lint. Therefore, some variability of fiber properties within samples is expected. These eight cottons were run daily during a 36-day period. For each cotton, eight replications for micronaire, length, tenacity, elongation, and color were performed at the beginning of each day on three different HVI instruments (two HVI 900 A, and one HVI 1000). This meant a total of 288 replications (36 days x 8 replications) per cotton per instrument.

Figure 1 Tensile strength tester: (a) fiber sample in a Pressley 1/8" clamp; (b) overview of the Testometric instrument with the Pressley clamp attachment; (c) broken fiber sample.

Results and Discussion

Relationship between HVI Elongation and HVI Tenacity

Figure 2(a) shows the relationship between the HVI elongation and the HVI tenacity for the 547 wild-type cotton samples (elongation % = $-0.302 \times \text{tenacity} + 15.27$, adjusted $R^2 = 0.131$, $F(1, 545) = 83.45$, $p < 0.00001$, standard error of estimate = 2.07). Figure 2(b) shows the relationship between the HVI elongation and the HVI tenacity of the 567 set of diverse genotypes (elongation % = $-0.2822 \times \text{tenacity} + 14.139$, adjusted $R^2 = 0.251$, $F(1, 565) = 190.85$, $p < 0.00001$, standard error of estimate = 1.09). These fig-

ures show that there is a weak negative correlation between fiber elongation and tenacity. However, this level of correlation does not preclude simultaneous improvement of fiber tenacity and fiber elongation. Indeed, these charts demonstrate that it is possible to have strong cotton (with a tenacity of 30.0 cN/tex) and simultaneously a good elongation (between 6 and 10%).

Work of rupture

Figure 3 shows a representative curve of load vs. elongation recorded with the tensile testing instrument (Testometric) for the 32 selected cotton samples as described in the Materials and Methods section. The first part of the

Figure 2 Elongation vs. HVI tenacity for: (a) 547 wild-type cotton samples; (b) 567 commercial varieties.

Figure 3 Representative load (in N) vs. elongation (in mm) curve.

curve between $l = 0$ and $l = l_0$ gives a measure of the crimp in the bundle. This needs to be removed from the curve to get an accurate bundle elongation measurement. Each curve has been inspected and the crimp removed before determination of tenacity and elongation. For tenacity determination, among the 32 cottons, the minimum coefficient of variation was 4.0% and the maximum was 11.6%, while for the elongation the minimum and maximum values of CV% were 5.2% and 12.0%, respectively.

We used different expressions to calculate the work of rupture (area under the curve) obtained from the tensile testing instrument:

- Stress, which is defined as the load divided by the area of the fiber cross-section [9]. The total cross-sectional area is the average cross-sectional area (without lumen) of individual fibers multiplied by the number of fibers in the bundle. The average cross-sectional area was obtained from the AFIS (area = H/e , with H = fineness in mtex, and p = cell-wall density in g/cm^3 , so $p = 1.52 \text{ g/cm}^3$) [10]. The number of fibers in the bundle was obtained from the mass of the bundle divided by the mass of 15 mm of fibers obtained from the AFIS fineness. 15 mm represents the width of the Pressley clamp with 1/8" spacer. The stress is expressed in N/m^2 (or Pascal, Pa). Furthermore, to take into account the length of the specimen, the elongation is expressed as tensile strain (elongation/initial length). Therefore, the curves load vs. elongation become stress vs. strain by a change of unit without affecting the shape of the curves. The work of rupture calculated from the stress-strain curve is equivalent to the energy calculated from the force-elongation curve in Joules divided by the product of the cross-section of the fiber (expressed in m^2) and the initial probe length (expressed in m). Therefore, the work of rupture denoted W_S could be expressed in $(\text{N m})/(\text{m}^2 \text{ m})$, which is equivalent to MPa.
- The load is divided by the number of fibers in the specimen, which is calculated from the mass of the specimen in milligrams and the corresponding AFIS fiber fineness in mtex. The work of rupture calculated from the load per number of fibers is expressed in cN/fiber and denoted $W_{N/f}$.
- The specific stress, which is the load divided by the mass in mg of the specimen and which is expressed in cN/tex and denoted W_{SS} .

The curves W_S , $W_{N/f}$, and W_{SS} were obtained from the tensile testing instrument and plotted. Each of the 32 samples was replicated 50 times. Then, each curve was fitted with the following function [11]:

$$F = a \exp \left[-\frac{\ln(2)}{\ln(d)^2} \ln \left(\frac{(x-b)(d^2-1)}{cd} + 1 \right)^2 \right] \quad (1)$$

where F represents the stress, load/fiber, or specific stress, x represents the strain, a represents the amplitude of the curve, b represents the value at maximum strain, c is the full width half mean, and d is the asymmetry at half-maximum. The work of rupture is calculated as the area under the curve between 0 (after crimp removal) and the elongation corresponding to the peak load.

The examination of the behavior from the tensile curves load–elongation revealed that we could approximate their shapes by a right triangle, with the base being the elongation and the height being the peak load. Therefore, as the HVI does not provide the load–elongation curves, the product tenacity $\times$ elongation should be proportional to the work of rupture. The “work factor” was calculated for the 32 cottons. An average value of 0.4 was obtained. This value is lower than the value reported by Meredith [6] (average 0.47). This difference could be attributed to the fact that in our experiments the load and elongation were determined on bundles of fibers while in Meredith’s experiments the load and elongation were determined on single fiber.

Relationship between work of rupture and the product tenacity $\times$ elongation HVI

The work of rupture W_S , $W_{N/f}$ and W_{SS} were correlated to the product tenacity $\times$ elongation as determined by HVI (Figures 4(a)–(c)). The following relationships were established:

$$W_S = 4.07 + 0.0060(\text{tenacity} \times \text{elongation}) \quad (2)$$

adjusted $R^2 = 0.897$, $F(1, 30) = 271.64$, $p < 0.0001$, standard error of estimate = 0.579,

$$W_{N/f} = 0.000194 + 0.000008(\text{tenacity} \times \text{elongation}) \quad (3)$$

adjusted $R^2 = 0.874$, $F(1, 30) = 216.16$, $p < 0.0001$, standard error of estimate = 0.00009,

$$W_{SS} = 0.2708 + 0.0039(\text{tenacity} \times \text{elongation}) \quad (4)$$

adjusted $R^2 = 0.894$, $F(1, 30) = 263.40$, $p < 0.0001$, standard error of estimate = 0.0384.

All coefficients of determination are good and confirm the above assumption. Equation (4) derived from Figure 4(c) was used to estimate the HVI work of rupture and to build the chart shown in Figure 5. In this chart, the change in work of rupture reported on the Y-axis was calculated using an HVI elongation of 6% and an HVI tenacity of 24 cN/tex as bases. This chart illustrates the impact of elongation on work of rupture. Indeed, improving the tenacity while decreasing the elongation could lead to a decrease in work of rupture. For example, a variety A having a HVI

Figure 4 Work of rupture (a) W_S , (b) $W_{N/f}$ and (c) W_{SS} vs. the product tenacity $\times$ elongation. Tenacity and elongation are determined with a HVI.

tenacity of 28 cN/tex and 4% elongation would have a work of rupture 15% lower than the base. In contrast, no improvement in fiber tenacity and an increase in elongation could result in a higher work of rupture value. As an example, a variety B with tenacity of 24 cN/tex and an improved elongation of 8% would have a work of rupture

Figure 5 Percentage change of work of rupture (W_{ss}) vs. HVI tenacity calculated for a HVI base set at 23.5 cN/tex and 6% elongation.

23% higher than the base. Therefore, variety B would perform better in spinning and weaving than variety A. Nevertheless, variety A would receive a monetary premium because the current marketing system does not take elongation or work of rupture into account. It is, therefore, necessary to document the benefit for the cotton industry of cotton varieties having improved elongation and better work of rupture.

Ability of HVIs to produce reliable elongation data

The above information confirms that an HVI measurement of elongation would be beneficial for cotton breeding programs and textile processing. Therefore, there is a need to confirm the ability of the HVI to produce reliable elongation data. The first step was to detect possible long-term trends or drifts of the HVI tensile measurements. A simple chart of the means of repeated measure over time is probably not adequate to detect patterns and trends. Therefore, an exponentially weighted moving average was calculated for each HVI instrument evaluated. This moving average function is a generalization of the simple moving average.

Using this function, each data point for the plot could be computed as follows:

$$Z_t = \lambda \bar{x}_t + (1 - \lambda)Z_{t-1} \quad (5)$$

The parameter λ should assume values greater than 0 and less than 1. This method of averaging specifies that the weight for historically 'old' sample means decreases geometrically as one continues to draw samples. In addition of smoothing the pattern of means across samples, this type of moving average allows trends to be more easily detected [12]. Figures 6(a) and (b) illustrate the results (with $\lambda = 0.1$) for HVI 1. They reveal an excellent stability of the instrument during the test period. There is no perceivable drift. Similar results were observed on the other two instruments (36 consecutive working days, data not shown). Therefore, the three instruments have a good precision (they can reproduce the same measurement results time after time). As the accuracy of the instruments can not be assessed because the true value of the eight bales are not known, the second aspect of this experimentation was to evaluate the differences between instruments. Figures 7(a) and (b) show the relationships between the three HVIs for tenacity and elongation (HVI 2 and HVI 3 are compared to HVI 1). The data points shown are averages of 36 days of testing. It appears that the correlations between instruments for both parameters are excellent. However, as clearly shown in Table 4, slopes and offsets are not equal to 1 and 0, respectively. It should be pointed out that, within the range of interest for tenacity (24.5–33.4 cN/tex; 97.4% of the U.S. Upland cotton crop in 2005 was in this range according to Cotton Incorporated U.S. Crop software [13]), the variations between machines are within an acceptable range. If HVI 1 gives on average 24.53 cN/tex, HVI 2 will be at 25.9 cN/tex, and HVI 3 at 25.0 cN/tex. For stronger cotton, if HVI 1 gives on average 33.4 cN/tex, HVI 2 will be at 32.8 cN/tex, and HVI 3 at 32.2 cN/tex. For elongation, the situation is somewhat different. Because of the lack of HVI calibration for elongation, HVI elongation is not reported by the current United States Department of Agriculture (USDA) classing system. Thus, we cannot assume what the dominant HVI elongation is. Neverthe-

Table 4 Summary of the linear regressions between HVIs.

	Intercept	Slope	Adjusted R^2	F test (1, 6)	Probability
Elongation					
HVI 2 vs. HVI 1	-0.307	0.870	0.983	410.0	0.00001
HVI 3 vs. HVI 1	1.722	0.683	0.960	168.4	0.00001
Tenacity					
HVI 2 vs. HVI 1	9.11	0.693	0.946	124.3	0.00001
HVI 3 vs. HVI 1	5.12	0.815	0.999	488.7	0.00001

Figure 6 Moving average for: (a) HVI tenacity; (b) HVI elongation.

less, in the breeding programs, elongation is in general comprised of values between 4 and 9%. If we assume this to be the range of interest for elongation, when HVI 1 gives an average elongation of 4%, HVI 2 would be at 3.2% and HVI 3 at 4.5%. For 9% elongation with HVI 1, HVI 2 would be at 7.5% and HVI 3 at 7.9%. These differences between instruments are too large and confirm the need to integrate a calibration routine for HVI elongation. Therefore, cotton standards for HVI elongation measurements have been created, which will ensure reliable elongation data. Then, using carefully selected cotton genotypes with a range of bundle tenacity and elongation, we will relate tensile properties (tenacity, elongation, and work of rupture) of raw cotton fibers to tensile properties of yarn. This study is ongoing and the results will be reported in a future publication.

Figure 7 (a) Fiber tenacity measured by HVI 2 and HVI 3 vs. fiber tenacity measured by HVI 1. (b) Fiber elongation measured by HVI 2 and HVI 3 vs. fiber elongation measured by HVI 1.

Conclusions

Cotton breeding programs must deliver fibers that perform better in textile manufacturing in order to compete effectively with the various man-made fibers and with international growths of cotton. While the improvement of fiber tenacity has been for many years the focus of these programs, elongation has not been included because calibration cottons are lacking. Yet, the work of rupture (of a bundle of fiber or yarn) is critically important and is determined by both tenacity and elongation. In this study, tenacity and elongation were measured using a modified tensile testing instrument. The corresponding work of rupture was calculated from the load vs. elongation curves. The results showed that the combination of increased fiber tenacity and decreased elongation results in significantly decreased work of rupture associated with a cotton cultivar. However, if the tenacity is kept the same and the elongation is increased, the work of rupture is increased significantly.

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