FAVIMAT ANALYSIS OF SINGLE COTTON FIBERS

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Abstract

The Favimat, a single fiber-testing machine, was used to quantify affects of cotton crimp on fibers from 3 cotton bales. These 3 bales consisted of cotton containing a low, high, and ideal micronaire for textile processing. In order to get a better representation of all fibers within these bales the cotton was further divided into the Suter-Webb array length groups. Prior to testing, individual cotton fibers were removed from each length group and pre-tensioned with a 50 mg clip in the Favimat. An opto-electrical sensor on the Favimat captured the image of each fiber for crimp analysis prior to testing. Following cotton crimp image capturing, fiber fineness was determined by the vibroscope method. A gauge length of 10 mm and a crosshead speed of 20 mm/min were used in tensile testing. Single fiber Favimat testing proved tedious but did produce comparable fineness, elongation, and tenacity results in a relatively short period of time. Future experimentation with a Favimat robot coupled with modifications in parameters could simplify testing. The mean values for these bales indicate that those varieties containing more crimp in the fiber leads to a larger elongation, force to break, linear density, tenacity, and work to rupture. The 7 length groups from these bales indicate that longer cotton fibers appear to contain more crimp per cm. A comparison of single and bundle fiber results appear to show the same trends with Favimat values generally larger than Stelometer, HVI, and Fibronaire values except for HVI tenacity. Based on a variety of testing procedures, the results suggest that the Favimat appears satisfactory for measuring current and future cotton properties.

Introduction

Once-over cotton harvesting removes all cotton bolls from the plant (Metzer et al., 1994) with mature cotton bolls found near the base and stem of the plant and natural variations of immature cotton bolls throughout the plant (Steadman, 1997). Cottonseed hairs (fibers) are removed, separated, and cleaned from cotton bolls by ginning to form cotton bales containing fibers from the entire plant. Cotton bales used in textile processing may contain diverse cotton fiber varieties grown on differing soils, under different environmental conditions, with varying fertilizer application rates, and harvested at different rates. Textile processing requires these diverse cotton bales to be blended, cleaned and processed, aligned, drawn, and twisted to form a uniform yarn. Yarn strength is determined by fiber strength and fiber interactions, including length, friction, and twist (Hsieh, 1999). Attempts have been made to correlate yarn strength and single fibers (Sasser et al., 1991). Yarns typically utilize approximately 30 to 70% of single fiber strength (Hsieh, 1999). With increased processing speeds, cotton fiber classification improvements are required.

Cotton grading has progressed from subjective human classers to the HVI, a high volume instrument. Prior to the HVI, classical cotton fiber properties such as strength, elongation, and fineness were generated using the Pressly tester, Stelometer, and Fibronaire. Bulk testing of multiple cotton fibers with the HVI has led to an understanding of 75% of the cotton fiber properties in end product processing (McAlister, 2000). HVI and Stelometer tests physically test a specially combed fiber bundle. Fibronaire and HVI measurements of fineness use known weights of cotton fibers. The Favimat (Textechno Herbert Stein GmbH & Co. KG, Mönchengladbach, Germany), a low volume single fiber-testing instrument, provides single fiber values, which are not currently generated in cotton grading that tests fiber bundles.

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Prior to the Favimat, Textechno in Germany has produced single fiber testers since 1955 (Morschel, 1999). Dedicated single fiber testing instruments have progressed from the Dewey single fiber tester (Dewey, 1913) to today's instruments the Favimat and Mantis® (Zellweger-Uster, Charlotte, NC). The Favimat provides traditional single fiber data, tensile strength and percent elongation at a constant rate of extension with additional fiber parameters such as capturing fiber crimps, tenacity, linear density, and work to rupture in approximately 35 seconds (Unknown, 1997). It was developed and is currently used for testing the consistency of synthetic fiber production (Morschel, 1999) with its potential use in cotton testing unknown. Fibers may be manually or mechanically loaded (Bader et al., 1997) into the Favimat. The Favimat has the capability to test and differentiate single fibers based on tensile strength, fineness, crimp extension, crimp rigidity and crimp number on the same fiber section (Schneider et al., 1998; Stein and Morschel, 1998).

Many events impact cotton fibers, so a better understanding of the consequences is desired to expedite processing in textile mills and to encourage certain cotton varieties. Reversals and convolutions are interrelated so that a cotton convolution occurs when many cellulose layer reversals overlap (Hsieh, 1999). Upon drying, the convolution angle of cotton fibers increases which decreases the force to break these fibers (Betrabet and Iyengar, 1964). Shenai (1988) declares that cotton spins better with more convolutions and Afzai (1980) believes cotton breeders should try and develop new convoluted varieties. A fusion of convolutions and reversals results in cotton crimp.

Cotton hairs grow to various lengths from cells on the seed to form elongated tubular shapes that appear as solid rods (circular cross section). These fibers are not solid, but hollow, and twist and crimp when dried. Often overlooked, fiber crimp, waviness, or kinkiness is a known fiber parameter that affects fiber cohesion (Morton et al., 1993). Crimp is a characteristic of all cotton fibers and determines the capacity of fibers to adhere under light pressure. The consistency and coherence of card webs, sliver, and roving, along with the strength and hairiness of yarn are all affected by a fiber's crimp. Crimp has been measured as number of crimps/cm or as a percentage increase in extent of the fiber on removal of the crimp (Morton et al., 1993). The number and frequency of convolutions and reversals may be a function of the environment (Moharir et al., 1979). Growth conditions endured by cotton plants may influence the crimp found in cotton hairs.

Cotton fiber development commences and develops in known order. Following flowering, each individual cell expands longitudinally for 25-35 days (Lord, 1981). The ultimate length is determined by the cotton variety and environmental conditions. During this growth the cells are encircled by a primary cell wall and covered by a waxy layer or cuticle (Lewin and Pearce, 1998). A secondary wall begins inside the primary wall as each fiber reaches its maximum length solidifying for 30-50 days (Lord, 1981). Cellulose in the crystalline state begins to form 15-19 days postanthesis and by maturity tubular fibers contain 96 % cellulose (Lewin and Pearce, 1998) with 90% in the secondary wall (Kohel, 1999).

Immature fibers have thin secondary walls while mature fibers have secondary walls approaching maximum thickness (Morton et al., 1993, Lewin and Pearce, 1998). Shorter cotton fibers are often considered weak and immature with a less circular cross section and low linear density (Petkar et al., 1977). Fibers of a higher maturity level demonstrate higher strength and linear density than immature fibers (Hsieh, 1999). Cellulose molecules run parallel along the axis of the fiber (Farr and Sisson, 1934) with Lewin and Pearce (1998) stating the secondary wall, which forms the main body of the fiber, consists of nearly parallel fibrils laid down concentrically in a spiral formation. Two layers are deposited daily in opposite directions with a dense layer deposited at night and a less dense layer during the day (Shenai, 1988). Cellulose molecules make up the cell walls forming crystalline microfibrils that are arranged in a complex multilayer structure (Farr and Sisson, 1934, Lewin and Pearce, 1998). Strength and elongation increases with increasing crystalline microfibril spiral arrangement and orientation within cotton fibers (Shenai, 1988).

Mature cotton bolls dehisce, which exposes the fibers to prevailing environmental conditions (Lewin and Pearce, 1998). Upon dehiscing, seed fibers lose their moisture causing them to collapse, curl, and wrinkle producing folds, convolutions (twists), and compression marks in the fiber (Ramey, 1982, Lewin and Pearce, 1998). Dehydration of the spiral wall structure creates a distorted cross-sectional area, which causes the fiber to twist about its axis forming a twisted and convoluted ribbon (Ramey, 1982, Waterkeyn, 1985, Lewin and Pearce, 1998, Hsieh, 1999). All fibers lose their circular cross-sectional shape when dried, but immature fibers generate pronounced cross-sectional differences from mature fibers (Lewin and Pearce, 1998). Coarse cotton fibers typically have fewer convolutions than fine fibers with fiber friction increasing with convolutions (Hussain and Nachane, 1998). Basu et al. (1978) have demonstrated that frictional characteristics of cotton fibers are dependent upon the occurrence of convolutions.

The uneven exterior of a dry cotton fiber's structure contains parallel wrinkles at a slight angle to its axis (Waterkeyn, 1985). The formed helical structure directly relates to fiber reversals, random inversions of fiber wrinkles as described by Waterkeyn (1985), and convolutions, twists of a fiber through 180° about its axis as described by Meredith (1951). These reversals are related to the orientation of secondary walls (Hsieh, 1999) and represent zones of variation in breaking strength (Lewin and Pearce, 1998, Hsieh, 1999). Regions adjacent to these reversals are constricted of a lower density and the weak point of the fiber rather than the reversal itself (Hsieh, 1999). Increases in cotton convolutions have been linked to an increase in fiber strength (Cho et al., 1996, Hsieh, 1999).

The objective of this study was to evaluate testing procedures and results generated by the Favimat, a new single fiber instrument. Cotton bales of 3 different micronaire were selected to cover a range of cotton fineness and to determine if different micronaire values influenced single fiber results. Favimat analysis of crimp has shown to be advantageous for synthetic crimped fibers with this study exploring if cotton results could be generated.

Materials and Methods

Southeastern growth cotton harvested in 1998 and 1999 with bales numbered 63117, 60135, and 103098 were used in this study. These cotton bales differ in fineness as measured by the micronaire method, and were all harvested, ginned, and baled by commercial methods (see Table 1 for official USDA, ARS, AMS HVI data). These 3 bales were chosen for their micronaire diversity because each bale represented a low (3.7), ideal (4.3), or high (5.4) micronaire for textile processing. For ease of classification, these cotton bales are referred to as I (bale no. 63117), II (bale no. 60135), or III (bale no. 103098). Prior to testing, all cotton samples were conditioned for at least 48 hours at 65 % RH and 21 °C (ASTM, 1997d).

Picking a single fiber from cotton samples often results in selecting the mature, long, and strong fibers that are often the easiest to separate. In order to get a better representation of all fibers within these bales, the cotton was further divided into the Suter-Webb array length groups (ASTM, 1997e). A Fibroliner FL101 (Peyer Electronics, Spartanburg, SC) was used to help separate the fibers (ASTM, 1993). For fiber alignment, a 90 mg sample was inserted into the Fibroliner FL101 to be combed and sorted twice. Following fiber alignment, two pulls were performed on this fiber beard removing the longest fibers. Fibers were removed from the combs and placed on a black velvet board to be measured with a Suter-Webb array ruler graduated in 0.3175 cm. Again and again, these pulls removed the longest fibers remaining in the fiber tuft allowing fiber separation and storage into Suter-Webb array length groups 7, 9, 11, 13, 15, 17, and 19. All fibers shorter than 0.9525 cm were placed in length group 7.

The Favimat measures the amount of force required to break up to 210 cN with a resolution of 1x10-4, while the fineness of these same fibers can be measured from 0.5 to 200 dtex. In a manner similar to the Mantis®, tensile strength is determined using a constant rate of extension. A gauge length of 10 mm and crosshead speed of 20 mm/min under a pretension of 0.20 cN/tex was used in testing. Fiber fineness is determined by the vibroscope method (ASTM, 1997c). Crimp number and amplitude are determined through an opto-electrical sensor that evaluates the fiber under a 0.03cN/tex. Twenty-five fibers from each bale and each different length group were tested twice using the Favimat Standard Tensile Test procedure (Textechno, 1999). After loading, the testing period was approximately 35 s per fiber.

For Favimat single fiber testing and ease of separation, a small tuft of fibers from one length group was laid onto a black velvet board. Using forceps, a single fiber was randomly separated from the group of fibers and a small clip weighing 50 mg was attached to the far end of the fiber. Forceps were used to grasp the opposite end of the fiber for Favimat mounting. The 50 mg clip kept the fiber straightened under constant tension for securing the fiber into the Favimat. The upper Favimat clamp was closed which suspended the fiber and clip. Both upper and lower clamps had a clamping surface area 16 mm^2 with a soft and hard rubber face. Closing the bottom Favimat clamp initiates Favimat single fiber testing.

For single and bundle fiber comparisons, additional cotton fiber property measurements were performed. For fiber fineness, the Fibronaire measures the resistance of a plug of cotton fibers to airflow (ASTM, 1997a). Determination of fiber fineness was performed on 3 bales divided into their respective length groups with 50 gr from each length group tested 3 times. Fiber tenacity and elongation were determined for these 3 bales and respective length groups using a Stelometer, a pendulum type instrument performed at a constant rate of loading (ASTM, 1997b). Stelometer tenacity and elongation measurements were performed on each length group using 6 fiber bundles. The HVI records micronaire values in a manner similar to the Fibronaire based on the resistance of a plug of cotton fibers to airflow with fiber bundle tenacity and elongation recorded at a constant rate of extension (ASTM, 1999). HVI data was supplied by USDA ARS AMS in Memphis, TN and performed on 4 separate samples taken from each cotton bale.

The data were statistically analyzed with the General Linear Models procedure in SAS using Duncan's New Multiple Range Test ($P<0.05$) to detect differences between means (SAS Institute Inc., 1985).

Results

Single fiber Favimat procedures were tedious but did produce comparable fineness, elongation, and tenacity results in a relatively short period of time. Manually separating the fibers into their length groups, preparing the fibers for testing, and loading the fibers into the Favimat were the most difficult and time-consuming processes. Future studies with the new robotic portion of the Favimat would help streamline the process. Once the fiber was loaded no intervention occurred with all testing performed sequentially on the same fiber section. The Favimat is self-contained to test fiber fineness, tenacity, force to break, work to rupture, and crimp as a reasonable method for gathering single cotton fiber data. Modifications to current testing parameters present potential for additional research as does further single fiber Favimat tests such as crimp stability and crimp extension.

A small sample size in each bale, approximately 50 fibers per length group, provided single fiber properties for 3 cotton bales (Table 2). With such a small sample size length groups only begin to form a trend. Bale III typically provided the largest fiber properties followed by bale II and bale I. In order to better visualize this trend, Suter-Webb array length groups 7, 9, 11, 13, 15, 17, and 19 were all combined into their 3 respective bale categories to evaluate bale differences. Assessed Favimat fiber quality parameters for the 3 bales tested in this study are listed in Table 3.

Measuring single cotton fibers on the Favimat showed that the force to break the cotton significantly increased from bale I thru bale III. Bale I had the lowest mean force to break of 3.86 g followed by bales II and III with respective mean force to break values of 4.34 and 5.20 g. Bale I elongated the least, 7.42%, followed by bale II, 9.04% and bale III, 9.51%. Single fiber elongation values from bales II, and III were significantly different from bale I. Subsequently in evaluating work to rupture, samples from bales I, II, and III were statistical different increasing from bale I (0.16 g*cm) to bale II (0.22 g*cm) and to bale III (0.27 g*cm). Fiber fineness measured by the vibroscope method indicated linear density increased from 1.66 dtex in bale I to 2.19 dtex in bale II and to 2.25 dtex in bale III. Linear density of bale I was significantly different from bales II and III. While these linear density values were unlike traditional airflow principals, they confirmed the same fiber fineness progression. As expected, these results indicate that force to break, fineness, and elongation of single fibers are closely related. Tenacity increased from 20.91 gforce/tex for bale I to 23.25 for bale II and 24.54 for bale III.

Convolutions and reversals in cotton fibers create a fiber crimp that statistically increased from bale I (11.38 crimp/cm) to bale II (12.34 crimp/cm) and to bale III (12.76 crimp/cm). The bales influenced the measured Favimat parameters with statistical differences existing between the three bales. Single fiber properties appear to be a function of cotton variety and possibly crimp. Crimp is known to affect friction and thus drafting and yarn processing. Yarns are influenced by frictional properties and less hairy if highly crimped fibers are utilized. The mean values for these 3 bales indicate that cotton containing more crimp in the fiber leads to a larger elongation, force to break, linear density, tenacity, and work to rupture. Evaluation of these mean values appears to indicate that a simple linear or polynomial relationship exists between cotton crimp values and measured fiber properties.

Bales I, II, and III were all combined into 7 respective length groups (7, 9, 11, 13, 15, 17, 19) to evaluate tested results. The outcome of these 7 Suter-Webb array length groups on Favimat single fiber analysis is shown in Table 4. After combining all bales and separating them based on their length groups, no statistical differences occurred among linear density and elongation values. Among force to break values length group 11, 4.82 g, was the strongest and statistically different from the weakest length group 13, 4.12 g. Evaluation of single fiber tenacity illustrated length group 7 had the highest tenacity of 24.57 gforce/tex and was significantly different from length group 13 with 20.72 gforce/tex. Length group 11 had the largest work to rupture of 0.242 g*cm which was significantly different from length group 13 value of 0.196 g*cm.

Measurement of crimp properties showed that length group 19 with 12.89 crimp/cm was the largest and was significantly different from length groups 7 (11.77 crimp/cm), 9 and 11 (12.13 crimp/cm), and 13 (11.97 crimp/cm). The mean values for these 7 length groups indicate that cotton containing more crimp in the fiber may be related to longer fibers. Evaluation of these mean values appears to indicate that a simple polynomial relationship exists between cotton crimp values and fiber length. Favimat single fiber properties combined together into short, fibers 1.60 cm and less, or long fiber categories, those fibers greater than 1.60 cm, demonstrate no statistical differences. Fibers 1.6 cm and less have a force to break of 4.65 g, crimp of 8.66 crimp/cm, and linear density of 2.05 dtex. Longer fibers have a force to break of 4.37 g, crimp of 8.76 crimp/cm, and linear density of 2.05 dtex. The lack of a trend or variation among length groups confirms that to provide the greatest benefit additional work must be performed with other cotton samples in order to determine if the crimp influences fiber properties.

Cotton fiber tenacity, elongation, and fineness values were generated using the HVI, Stelometer, Fibronaire, and Favimat (Table 5). Excluding the Favimat, these instruments measure fiber properties on a fluffy mass of cotton fibers. As expected no differences were found between the HVI and Fibronaire fineness values. Favimat linear density results were statistically different from the HVI and Fibronaire results. Increasing from bale I thru bale III the Favimat demonstrated the same fineness trend with bales statistically different. Fineness values generally show the same trend creating an offset at a level of 0.69 between HVI and Favimat fineness. Statistical differences in fiber elongation were found to exist between bales and testing methods. Elongation of the cotton fibers was statistically different between cotton bales in addition to Favimat and Stelometer testing methods. Both testing methods displayed the same trend among bales with Favimat elongation values significantly larger with an offset at a level of 2.24 between Stelometer and Favimat elongation values. HVI produced the highest tenacity followed by the Favimat and Stelometer results. Tenacity values generally show the same trend creating an offset at a level of -3.58 between HVI and Favimat, at a level of −3.11 between HVI and Favimat, and at a level of −6.69 between HVI and Stelometer. Favimat tenacity results were significantly different among all bales while Stelometer results were indifferent. HVI fiber tenacity demonstrated that bale III was significantly larger than bales I and II and consistent with the Favimat trend.

Discussion

Cotton failure has been mainly studied as fiber bundles in cotton classification. Single cotton fibers have many potential weak points in its structure conceivably related to growing conditions and variety. Cotton exhibits different cellulose packing densities with lower convolutions, reversals, and crimps within coarse varieties (Patil, 1992). Cotton fiber strength differences are due to crystalline structure and convolution differences among varieties (Cheng and Duckett, 1974). Traditional fiber properties as well as crimp and linear density determinations on the same single fiber offer the potential for better fiber and yarn comprehension. Yarn evenness and strength is known to increase with fiber cohesion and may be a function of fiber crimp. As yarn frictional properties are better understood, this progression may initiate breeders to introduce other new cotton varieties. In our study, it appears that cotton varieties containing more crimp in the fiber leads to a fiber with a larger elongation, force to break, linear density, tenacity, and work to rupture. This agrees with work by Cho et al. (1996) and Hsieh (1999) who have shown increased cotton convolutions leads to increases in fiber strength.

In HVI and Stelometer testing, not all fibers are submitted to the same load due to fiber preparation and fiber crimp. A single fiber is prepared for the Favimat with the entire fiber section tested under the same load. Morton and Hearle (1962) have shown that finer cottons show a higher tenacity with elongation not related to fineness, while Favimat results indicate that fibers with more crimps have a higher linear density, tenacity, and elongation. Highly crimped fibers contain many convolutions and reversals that must undergo untwisting and extension during a test (Patil, 1992). Fibers with a higher crimp appear to have higher strength and may clarify why Shenai (1988) believes that highly convoluted cotton spins better.

Favimat results agree with tenacity and linear density correlation work performed by Patel and Patil (1975). Single fiber tests performed on the Mantis® and Instron have shown that as cotton fibers mature the breaking force, elongation, work to rupture, linear density, number of twists, and convolution angle increase (Hsieh, 1999). Fiber friction increases with convolutions so crimp appears important to understanding a yarn break because most fibers slip and a few fibers break. It is generally understood that commercial cottons contain the minimum crimp required for processing with some cottons demonstrating an increase in convolution with fiber length (Clegg and Harland, 1924). In our study, mean values for 7 length groups indicate that cotton containing more crimp in the fiber may be related to longer mature fibers.

Favimat measures the fineness directly on one fiber while other fineness measurements are performed on a bundle of fibers. For this study, no differences were found between the HVI and Fibronaire fineness values. Favimat results were statistically different from the HVI and Fibronaire but demonstrated the same trend in fineness. Favimat single fiber tenacity properties all exceeded 6.12 gforce/tex, the minimum tenacity required for fiber processing (Hsieh, 1999). Morton and Hearle (1962) imply that tenacity and elongation increases with longer cotton fibers, despite Favimat results exhibiting little or no tenacity or elongation increases with fiber length. Statistical differences in fiber elongation were found to exist between bales and testing methods. Fiber property discrepancies between single and bundle fiber tests are likely to occur due to cotton crimp. While differences in results exist, single and bundle fiber tests typically show a good correlation (Warrier and Munshi, 1982).

Conclusions

Crimp and other single fiber properties appear to be a function of cotton variety. The mean values from these bales appear to suggest that a variety containing more crimp in the fiber leads to a larger elongation, force to break, linear density, tenacity, and work to rupture. This data implies that a simple linear or polynomial relationship exists between cotton varieties, crimp values, and measured fiber properties. As expected, results obtained on fiber bundles and single fibers point toward typical interrelationships of strength, length, and fineness. Further assessment of this data appears to show that a simple polynomial relationship exists between cotton fiber length and crimp values. In addition, Favimat measurements of linear density and crimp count may prove helpful in predicting fiber strength for yarn processing. Regardless of measurement technique, fineness, elongation, and tenacity values displayed the same trend among bales with various offset values. Future research requires cotton varieties of diverse micronaire and length groups to determine cotton's ideal crimp and its association with synthetic fibers in textile processing. Crimped fibers require slightly less twist to form yarns and could help optimize production. Based on these testing procedures, the results suggest that the Favimat appears satisfactory for measuring current cotton properties. The results confirm the need for additional cotton variety, crimp analysis, and fiber microstructure research.

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Table 1. Official cotton bale classification data*.

Bale	Crop year	Mic	Strength	Color	Color quadrant	Rd
I	1998	3.7	26.0	41	3	73.5
II	1998	4.3	25.7	32	2	74.3
III	1999	5.4	27.6	42	2	72.5

Bale	Crop year	+b	Trash	UHM	UF	Leaf
I	1998	89.0	7	99.0	79.0	5
II	1998	95.0	5	103.0	80.0	3
III	1999	88.8	3	104.5	80.5	3

* USDA, ARS, AMS, Memphis, TN.

Table 2. Effect of Suter-Webb length group cotton fibers via Favimat.

Bale [a]	Length group [b]	Sample number	Force to break (g)	Elongation (%)
I	7	50	3.98 e,f,g*	7.05 g
	9	50	3.92 e,f,g	7.34 f,g
	11	50	4.01 e,f,g	8.03 d,e,f,g
	13	50	3.69 g	7.24 f,g
	15	50	3.71 g	7.38 f,g
	17	50	3.85 f,g	7.5 e,f,g
II	7	49	4.28 d,e,f,g	9.05 b,c,d
	9	50	4.75 b,c,d,e,f,g	9.18 a,b,c,d
	11	50	4.35 c,d,e,f,g	8.82 c,d,e
	13	49	4.37 c,d,e,f,g	9.11 b,c,d
	15	50	4.05 e,f,g	9.01 b,c,d
	17	50	4.46 c,d,e,f,g	9.14 b,c,d
	19	48	4.15 d,e,f,g	8.97 b,c,d
III	7	49	5.35 a,b,c	9.32 a,b,c,d
	9	48	5.13 b,c,d	8.53 c,d,e
	11	50	6.10 a	10.60 a
	13	50	4.29 d,e,f,g	8.87 c,d,e
	15	48	4.97 b,c,d,e	9.89 a,b,c
	17	48	5.69 a,b	10.48 a,b
	19	50	4.89 b,c,d,e,f	8.87 c,d,e

	Length	Sample	Linear	Tenacity
I	7	50	1.70 c	23.40 b,c,d
	9	50	1.71 c	22.66 b,c,d
	11	50	1.73 c	23.66 b,c,d
	13	50	1.66 c	22.13 b,c,d
	15	50	1.54 c	23.76 b,c,d
	17	50	1.58 c	23.88 b,c,d
II	7	49	2.28 a,b	19.77 d
	9	50	2.15 a,b	22.55 b,c,d
	11	50	2.06 b	21.40 b,c,d
	13	49	2.28 a,b	21.01 c,d
	15	50	2.11 a,b	19.70 d
	17	50	2.31 a,b	21.51 b,c,d
	19	48	2.17 a,b	20.38 c,d
III	7	49	2.16 a,b	30.56 a
	9	48	2.36 a	22.13 b,c,d
	11	50	2.31 a,b	27.40 a,b
	13	50	2.28 a,b	19.01 d
	15	48	2.36 a	22.73 b,c,d
	17	48	2.19 a,b	26.38 a,b,c
	19	50	2.11 a,b	23.64 b,c,d

	Length	Sample	Work to	Crimp
I	7	50	0.16 f,g	11.23 e,f
	9	50	0.17 f,g	11.66 c,d,e,f
	11	50	0.18 e,f,g	10.95 f
	13	50	0.15 f,g	11.29 d,e,f
	15	50	0.15 f,g	11.51 c,d,e,f
	17	50	0.17 f,g	11.63 c,d,e,f
II	7	49	0.22 c,d,e,f	11.71 c,d,e,f
	9	50	0.24 c,d,e	12.15 b,c,d,e
	11	50	0.22 c,d,e,f,g	12.83 a,b
	13	49	0.22 c,d,e,f,g	12.22 a,b,c,d,e
	15	50	0.20 d,e,f,g	12.62 a,b,c
	17	50	0.21 c,d,e,f,g	12.40 a,b,c,d
	19	48	0.21 c,d,e,f,g	12.43 a,b,c
III	7	49	0.27 a,b,c	12.37 a,b,c,d
	9	48	0.25 c,d	12.60 a,b,c
	11	50	0.33 a	12.62 a,b,c
	13	50	0.21 c,d,e,f,g	12.40 a,b,c,d
	15	48	0.27 b,c	13.02 a,b
	17	48	0.32 a,b	13.02 a,b
	19	50	0.25 c,d	13.32 a

[a] Cotton bales are referred to as I (bale no. 63117), II (bale no. 60135), or III (bale no. 103098).

[b] Seven length groups correspond to Suter-Webb length groups (ASTM,1993).

* Values followed by different letters within columns are significantly different, P<0.05, according to Duncan's New Multiple Range Test.

Table 3. Effect of different micronaire cotton bales on single cotton fiber properties via Favimat.

Bale	Sample number	Force to break (gforce)	Elongation (%)	Linear density (dtex)
I	300	3.86 a*	7.42 a	1.66 a
II	346	4.34 b	9.04 b	2.19 b
III	345	5.20 c	9.51 b	2.25 b

Bale	Sample number	Tenacity (gforce/tex)	Work to rupture (gcm)	Crimp (crimp/cm)
I	300	20.91 a	0.16 a	11.38 a
II	346	23.25 b	0.22 b	12.34 b
III	345	24.54 b	0.27 c	12.76 c

* Values followed by different letters within columns are significantly different, P<0.05, according to Duncan's New Multiple Range Test.

Table 4. Effect of Suter-Webb length group cottons on single cotton fiber properties via Favimat.

Length group[a]	Sample number	Force to break (g)	Elongation (%)	Linear density (dtex)
7	148	4.53 a,b*	8.46 a	2.04 a
9	148	4.59 a,b	8.35 a	2.07 a
11	150	4.82 a	9.15 a	2.03 a
13	149	4.12 b	8.40 a	2.07 a
15	150	4.24 a,b	8.76 a	2.01 a
17	148	4.65 a,b	9.02 a	2.03 a
19	98	4.53 a,b	8.92 a	2.14 a

Length group[a]	Sample number	Tenacity (gforce/tex)	Work to rupture (g*cm)	Crimp (crimp/cm)
7	148	24.57 a	0.216 a,b	11.77 b
9	148	22.45 a,b	0.219 a,b	12.13 b
11	150	24.15 a,b	0.242 a	12.13 b
13	149	20.72 b	0.196 b	11.97 b
15	150	22.06 a,b	0.204 a,b	12.38 a,b
17	148	23.89 a,b	0.231 a,b	12.34 a,b
19	98	22.04 a,b	0.227 a,b	12.89 a

[a] Seven length groups correspond to Suter-Webb length groups (ASTM,1993).

* Values followed by different letters within columns are significantly different, P<0.05, according to Duncan's New Multiple Range Test.

Table 5. Effect of single cotton fibers vs. bundles of fibers.

Cotton bale [a]	**HVI fineness [b] (micronaire)**	**Favimat fineness [c] (dtex)**	**Fibronaire fineness [d] (micronaire)**
I	3.7 a*	1.66 b	3.7 a
II	4.3 b	2.19 d	4.2 b
III	5.4 c	2.25 e	5.5 d,c
Mean	4.5 A	2.03 B	4.5 A

Cotton bale [a]	**HVI tenacity [b] (gforce/tex)**	**Favimat tenacity [c] (gforce/tex)**	**Stelometer tenacity [e] (gforce/tex)**
I	26.0 a	20.9 d	19.7 e
II	25.7 b	23.2 c	19.6 e
III	27.6 a,c	24.5 e	20.1 e
Mean	26.5 E	22.9 F	19.8 G

Cotton bale [a]	**Favimat elongation [c] (%)**	**Stelometer elongation [e] (%)**
I	7.42 a	5.87 d
II	9.04 b	6.57 e
III	9.51 c	6.83 e
Mean	8.7 C	6.42 D

[a] Cotton bales are referred to as I (bale no. 63117), II (bale no. 60135), or III (bale no. 103098).

[b] HVI fineness and fiber bundle strength of 3 bales determined according to ASTM (1999).

[c] Favimat single fiber linear density, elongation, and strength determined on cotton fibers separated into 7 length groups (ASTM,1993).

[d] Fibronaire (ASTM, 1997b) of 7 length groups evaluated for each fiber length group collection (ASTM,1993).

[e] Stelometer (ASTM, 1997b) fiber bundle strength and elongation for 7 length groups (ASTM,1993) evaluated for each fiber length group.

* Values followed by different lower or upper case letters are significantly different, $P<0.05$, according to Duncan's New Multiple Range Test.