ABSTRACT

DOH, SONG JUN. A study on the effects of textile processing on tensile properties of single cotton fibers - From raw cotton to washed garments (Under the direction of Moon W. Suh.)

Effects of textile processing on breaking strength, breaking elongation, morphological properties and dimensional properties were investigated and analyzed. Cotton varieties were obtained from fields and processed under various ginning and carding conditions into a T-shirts. The produced T-shirts were washed and dried repeatedly. A large number of fibers were collected at various processing stages and tested one by one by a Mantis® single fiber tensile tester. During repeated washing/drying experiment, progressive shrinkage in length, width, and area were measured. The surface characteristics of fibers in yarns from washed T-shirts were observed by a scanning electron microscope. It was found that the breaking strength and breaking elongation of cotton fibers were reduced substantially due to textile processing. A higher ginning rate generated a higher average breaking strength and a lower breaking elongation compared to that from a lower ginning rate. However, based on the fibers taken from washed and unwashed T-shirts, the higher ginning rate was shown to have produced a lower average breaking strength as well as breaking elongation compared to the case at lower ginning rate.

A higher carding rate adversely affected the tensile properties for entire range of the processes. Using of 2 lint cleaners at the gin resulted in a lower tensile properties than that of 1 lint cleaner.

Although the results were not statistically significant, use of 2 lint cleaners at gin

resulted in a lower average length shrinkage in T-shirts and more damage to the fiber surface after repeated washing/drying.

The progressive length shrinkage of the T-shirts during 32 washing/drying cycles was shown to be consistently higher for the higher ginning and carding rates. The progressive width and area shrinkage on the other hand did not show the effects of processing clearly. A limited microscopic study suggests that the number of lint cleaners in ginning may be the most significant contributor to fiber damage as shown by the broken fibrils and cracks on fiber surfaces.

A STUDY ON THE EFFECTS OF TEXTILE PROCESSING ON TENSILE PROPERTIES OF SINGLE COTTON FIBERS - FROM RAW COTTON TO WASHED GARMENTS

by
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DEDICATION

I would like to dedicate this dissertation and all of the work involved in completing it to my parents, Moo-Hoe Doh and Young-Ah Kim.

BIOGRAPHY

The author, SONG JUN DOH, the son of Moo-Hoe Doh and Young-Ah Kim, was born on December 21, 1974, in Seoul, Korea. He graduated from Young-Dong High School, Korea in February, 1993 and entered Seoul National University, Seoul in March, 1993. He received the Bachelor of Science degree in Textile Engineering in February, 1997.

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1 INTRODUCTION

The mode and extent of damages inflicted upon cotton fibers by mechanical actions during cotton ginning and the subsequent textile manufacturing processes have long been speculated but have not been carefully studied in the past.

Investigations on this important issue have not been successful due to lack of means for testing the tensile properties of a large number of cotton fibers before and after each stage of process. Yet, it is readily conceivable that the rapid and repeated loading may leave irreversible effects on cotton fibers. Loss of the fiber's "liveliness" for instance, through impairment of its elasticity, may be reflected in terms of certain latent changes in the stress-strain behavior of fibers, yarns and fabrics. More importantly, how these changes are manifested during the lifetime of a product is of great significance. The appearance, shape, luster, and dimensional stability of cotton clothing may be profoundly affected by the initial processing methods where varying degree of impact loading has been applied to the raw cotton. As one of dimensional properties, shrinkage of knitted T-shirts can be examined under repeated wash and wear in terms of the particular ginning and carding process parameters. Traditionally, however, the shrinkage of cotton fabrics has been studied in terms of either (1) relaxation of the residual stresses applied to the yarns during manufacturing, or (2) geometrical changes in the fabric structures brought about by changes in yarn diameter due to swelling during washing. These attempts by and large failed in the sense the theoretically predicted values were never sufficient for justifying the large variations in the experimental data. Without a theoretical connection or experimental evidence linking the morphology or mechanical properties of the fibers

directly to the shrinkage of cotton fabrics, any attempt to relate the two appears totally unsatisfactory.

As consumers began demanding quality of cotton-made goods over and above lower prices, it is time to reexamine the qualities of cotton products to see if indeed the speed of production has to be evaluated carefully in light of the possible adverse effects originating from fast processing. Therefore, it is prudent to study two major sources of fiber damage, namely, ginning and carding for each of their individual and combined effects on the resulting yarns and fabrics. This paper examines the possible relations between single fiber tensile properties and dimensional properties of garments and the effects of the speed of gin, card, and the number of lint cleaners.

Although HVI (High Volume Instrument) has been used generally for examining various properties of fibers from ginned cotton and card slivers[1-10], it is impossible to measure tensile properties of cotton fibers within yarns, fabrics, and garments by using HVI due to the restriction in sample preparation. This is a great obstacle which hinders broader application of HVI data to predict the properties of yarns with various counts.

Although the only way to measure the tensile properties of cotton fibers at post-carding process is single fiber test, it has not been as widely applied as HVI due to the extensive time and labor requirements. More recently, however, the invention of Mantis® single fiber tester made it possible to test individual fibers at reasonable cost and speed.

Single fiber tests also have significant advantages over the bundle tensile measurements. At every stage of spinning, fabric manufacturing, and even after repeated washing and drying of garment, it is possible to obtain single fiber samples for Mantis® testing.

For the above reasons, the changes in tensile properties from the opening process to the garment-consuming (repeated washing and drying of garments) step, may be measured and analyzed based on the results of tensile tests on individual cotton fibers. By assuming that the dimensional properties of washed garments are related to the tensile properties of constituent fibers, and that their properties are affected by the opening processes, tracking the single fiber tensile properties from the early process stages to washing steps would disclose the effects of the speed of the opening and cleaning processes on the quality of the end product.

2 LITERATURE REVIEW

There have been numerous studies performed on the effects of processing on cotton processing and various cotton qualities. This large volume of studies provides the evidence on the importance of the topic. The review of the literatures is divided into three parts. The primary part of this research concerns how the ginning and carding processes affect the fibers within repeatedly washed and dried knitted garments. For this reason, the studies made on the effects of ginning and carding on various properties of cotton fibers during processing have been reviewed. While many of the studies were focused on the length distribution of cotton fibers, which is considered to be one of the most important properties affecting the quality of the end product, the tensile properties of cotton fibers have not been studied effectively although they are critical for the processing efficiency and the dimensional properties of garments. The studies to date are mostly on the bundle fiber properties through Pressley and HVI testers. Due to the speed and cost of the testing methods, test for individual fibers were rarely performed.

In order to analyze the response of fibers to the mechanical impact during ginning and spinning, studies on the macrostructure of fibers and their effects on the mechanical actions were reviewed after repeated washing/drying of knitted garments, also.

The effects of repeated washing and drying of garment on tensile properties of fibers as well as the dimensional properties of a garment are of great interest. Several researchers studied about the effects of washing and drying on the dimensional properties of garments and surface characteristics of the fabrics. Hypothetically, the effects of the changes in processing rates could be detected from the fibers tested after repeatedly washing and drying of the garments. For this reason, references on the effects of washing and drying on dimensional properties of the fabrics were also reviewed.

2.1 Effects of Ginning and Carding on Cotton Fiber Properties

2.1.1 Quantification of Cotton Quality Changes in Terms of Fiber Processing Propensity

Since cotton industry was established, rigorous mechanical processing has been a necessity in order to successfully harvest, gin, open, clean, parallelize, and assemble cotton fibers into textile structures. All mechanical processing is a compromise between quality improvement (disentanglement and cleaning of fibers) and damage (neps, fiber breakage, and loss) [11-13]. This trade-off between cleaning and damage governs the efficiency of manufacture as well as the quality of the textile product [14]. Grant *et al.* [5] tested fibers from ginned cotton and from yarn of seven cottons of different physical properties as a bundle and as individual fibers in order to determine what changes in properties

could be attributed to the mechanical processing. They found that breaking load and weight-fineness of the fibers were essentially the same before and after processing and the significant difference between the unprocessed and processed cottons was noted in the values for elongation at break. They discovered that during the processing, the tension which stretched the fiber also removed kinks and produced a permanent deformation which may be repeated several times as fibers pass through opening, carding, and drawing machine. Leitgab *et al.* [15] investigated the effects of overdrying on the processing characteristics of cotton and to determine any changes in fiber properties relating thereto. They suggested that there was evidence to indicate a greater crystallinity for the heated cottons.

The principles and the mechanism of the carding process have been studied by several researchers [5, 11, 16-26]. Carding process separates the tufts into individual fibers, extracts foreign material, and begins the fiber alignment [16]. Lee *et al.* [19] did the study concerned with the effects of carding rate, draft, spindle speed, twist, and other production variables on the strength, uniformity, imperfections, and lint-shedding tendencies of ring-spun cotton yarns. They found higher carding rate improved fiber orientation and produced stronger, more uniform yarn. However, this study was limited to the yarn properties and did not extend to the fiber properties. Rakshit *et al.*[20] studied the influence of card production rate on the performance of open-end (OE) machine and yarn quality using two low-grade trashy cottons and a waste mixing containing a high proportion of noil. They found that a lower card production rate improved card cleaning efficiency, reduced trash level in sliver, achieved

better nep removal efficiency and brought down the opening roller waste on OE machine

2.1.2 Quantification of Cotton Quality Changes in Terms of Short Fiber Content and Fiber Length Characteristics

Since the principal overt manifestation of processing damage to cotton is fiber breakage, it is essential to have a methodology for measuring and interpreting incremental amounts of fiber breakage [14]. Griffin *et al.* [27] reported that lint cleaning significantly reduced fiber length and increased short fiber content (SFC). Dever *et al.* [28] investigated the influence of cotton fiber strength and fineness on fiber damage during lint cleaning. The objectives of the study were to determine if fiber strength or other fiber properties have an effect on the magnitude of fiber length reduction resulting from ginning and lint cleaning. They also investigated the relationship of neps created during ginning and lint cleaning relative to fiber properties. In their research, it was found that the fiber length deterioration from saw ginning was negatively correlated with fiber strength, and that the fiber breakage in lint cleaning was positively correlated with fiber fineness. However, an increase in neps due to lint cleaning was found to have no significant relationship to the fiber properties. Another researcher [29] tried to explain the relationship between ginning processing and nep count but failed to provide a definite conclusion. Griffin [27] showed that ginning with two lint cleaners at low fiber-moisture levels, as indicated by the SFC data, caused the greatest amount of fiber breakage. He observed that the greatest quantity of short fibers were generated at the 150% of normal ginning

rate, but the effects from high-ginning rates were secondary to the effects of ginning at low-moisture levels. Conclusively, he asserted that moisture in cotton and the number of lint-cleaning stages had more influence on SFC than did ginning rates or saw speeds.

As stated in the first paragraph, short fiber content and length properties are closely related to the fiber breakage. Although the fiber breakage is a conspicuous feature showing degradation of the fiber quality, it is impossible to find potential damages inflicted upon the fibers based on these properties, alone. For example, internal damage of the unbroken fiber is not exhibited by the length. Therefore, it is prudent to consider potential damages on fibers during textile processing in order to investigate the changes in fiber quality during repeatedly washing and drying of the end products. One of the methods for studying the fiber damage during textile processing is to study the structural characteristics of the fibers and relate them to the tensile properties. Following section deals with the literatures about the macrostructures of cotton fibers.

2.2 Effects of Structural Characteristics of Cotton Fibers on Tensile Properties

2.2.1 Fibrillar Structure of Cotton Fiber

Cotton fiber is known to have highly ordered structure. Manley [30] and other researchers found out that the microfibrils may have a thickness of only 35Å. This made it necessary to re-examine the concept that both ordered and

disordered regions are present. Hearle [31] suggested that plant fibers are composed of an assembly of fibrils, each of which is a single crystal made up of folded polymer chains. However, there is a piece of evidence which suggests that the fibers cannot be an assembly of completely separate fibrils. If the fibrils were independent of one another, there would be no reason why the swelling should stop as it does at a well-defined limited value. It therefore seems that there must be some tie between the fibrils with at least small lengths of polymer chains linking one fibril to one another. He studied the effect of helix angle of fibrils on the tensile properties of cotton fiber. The fibrils in cotton fiber were known to have spiral angle of about 30º to the fiber axis. He suggested two modes of deformation during fiber extension: either the fibrils may stretch as the fiber extends at constant volume or the fibrils may change their helical configuration, like spiral springs, without change in length but with a reduction in volume giving the resistance to fiber extension.

Considering the balance between the two modes of deformation comes in through the use of the principle of minimum energy. With this minimum energy principle, breaking strength, modulus, and breaking elongation were calculated in terms of the helix angle, local tensile modulus of fibril assembly, and local bulk modulus of fibril assembly.

In this analysis, the helix angle was taken as constant throughout the assembly and this assumption lead to uniform strain throughout the fiber thickness.

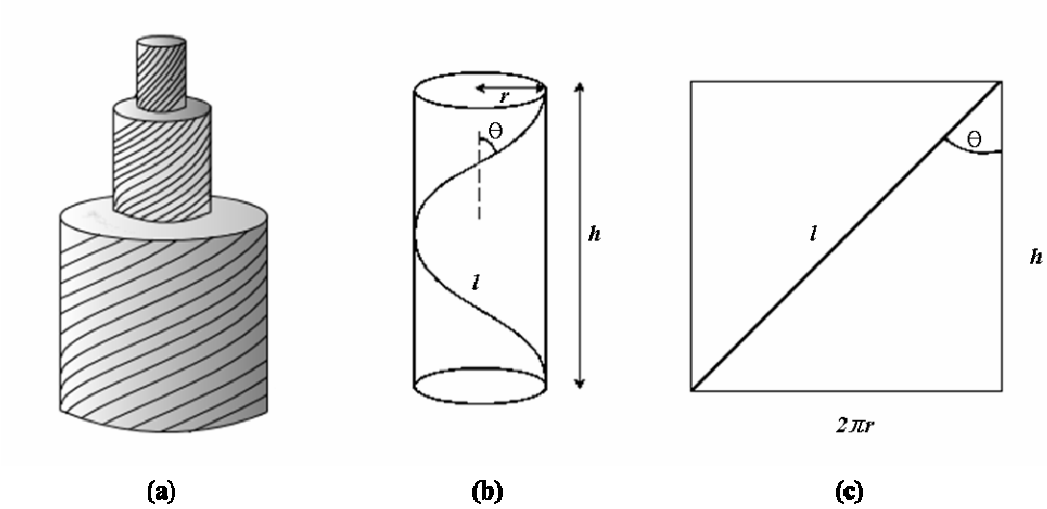

Figure 1. (a) Model of Cotton Fiber as an Assembly of Fibrils Following Helical Paths. (b) Path of a Single Fibril. (c) "Opened-out" Diagram.

He considered fibers to be made up of an assembly of fibrils, each following a helix of angle θ, as shown in Figure 1a. If we consider a length l, corresponding to one turn of the helix of radius r, Figure 1b, this can be represented by the diagram of the cylinder opened out flat as in Figure 1c. We then have:

$$l^2 = h^2 + 4\pi^2 r^2 \tag{1}$$

He assumed for simplicity that if the fibrils are extended independently, they would deform at constant volume. However, due to the helical arrangement of the fibrils, the fiber as a whole may reduce in volume during extension in order to relieve the tensile strain. By the derivation based on the above information, he calculated the following equations

$$\sigma = \frac{E_f \cos^2\theta \sin^2\theta + 2K_f}{E_f \sin^4\theta + 4K_f} \tag{2}$$

where

E_f = fiber Young's modulus (kg/mm^2)

K_f = bulk modulus (kg/mm^2)

σ_i = Poisson's ratio of a fibrillar layer

The stress f was given by the equation:

$$f = \delta U / \delta \varepsilon = E_f \varepsilon(\cos^2\theta - \sigma \sin^2\theta)^2 + K_f \varepsilon(1-2\sigma)^2 \quad (3)$$

And hence the fiber modulus E was given by:

$$E = E_f(\cos^2\theta - \sigma \sin^2\theta)^2 + K_f(1-2\sigma)^2 \quad (4)$$

If K_f is very large, then

$2K_f >> E_f \cos^2\theta \sin^2\theta$ and $4K_f >> E_f \sin^4\theta$, so that $\sigma = \frac{1}{2}$ and:

$$E = E_f(\cos^2\theta - \tfrac{1}{2}\sin^2\theta)^2 \quad (5)$$

The same reduction will occur when θ is very small.

The alternative reduction, when K_f is small and E_f is large, so that $E_f \cos^2\theta \sin^2\theta >> 2K_f$ and $E_f \sin^4\theta >> 4K_f$ gives:

$$\begin{aligned} \sigma &= \cot^2\theta \\ E &= K_f(1-2\cot^2\theta)^2 \end{aligned} \quad (6)$$

2.2.2 Inner and Outer Fibrillar Layers

Waterkeyn *et al.* [32] introduced the constant-gyre-length model, meaning the spiral angle of the fibrils decreased uniformly from the surface of the fiber to the core. They observed from fibers grown *in situ* that the cellulose fibrils in the first layer of the secondary wall are inclined at 55º to the longitudinal axis of the fiber. The next inner layer of the secondary wall is then laid down with a helical structure of fibrils inclined at 50º to the fiber axis. During the subsequent cellulose deposition, from day 30 to 59 postanthesis, the inclination of fibrils diminishes gradually to 20º or less. Warrier *et al.* [33], studied the relationships between orientation of fibrils and tensile properties of cotton fibers. They indicated that fibrils with different inclinations to the fiber axis have different extents of influence on a specific fiber property. Chidambareswaren *et al.* [34] found that cottons with smaller convolution angles registered noticeable orientation changes at small extensions, while highly convoluted cottons did not show this behavior. Orientation in mature cottons was found to respond better to extension than that in immature ones. In addition, the rate of change of orientation with extension depended upon the normal orientation, convolution angle, and maturity of the fibers.

From the above studies, we could establish a model for macrostructure of cotton fiber. Namely, cotton fiber is assumed to consist of two different layers: inner layer which is more oriented to the fiber axis and outer layer oriented less to the fiber axis.

2.3 Relationships Between Fiber Properties and Yarn Properties

In studying the response of cotton to stress forces, it is considered essential to investigate the properties of individual cotton fibers [35]. There have been numerous researchers who elucidated the relationship between fiber properties and yarn properties. Virgin and Wakeham [9] studied the single-fiber testing methods for the determination of cotton fiber properties and for the prediction of yarn quality. They stated that yarn strength depends strongly on fiber length, fineness, and elastic modulus, and only weakly on fiber strength; yarn elongation depends greatly on fiber elongation and elastic modulus. Fiber elongation was found to be the most important fiber property influencing yarn elongation. Unlike the conclusion of Virgin and Wakeham, Fiori *et al.* [21, 36] suggested that high-strength cotton produces stronger yarns than low-strength cottons for any given yarn number or twist, a well-known general relationship. They made several conclusions about the effect of cotton fiber strength on single yarn properties and on processing behavior; the strength of the fiber has little or no effect on processing efficiency through spinning. High-strength cotton produced stronger yarns than low-strength cottons for any given yarn number or twist, a well-known general relationship. The amount of twist required to obtain maximum strength in single cotton yarns is not affected by fiber strength. Fiber strength does not significantly affect the uniformity of slivers, rovings, or single yarns. Fiber strength does not significantly affect yarn elongation

The positive correlation between fiber strength and yarn strength were supported by other researchers [37-39]. From the research of Ramey *et al.* [37], fiber

tenacity was positively correlated with yarn tenacity. The correlation coefficients were the largest of any of the fiber properties except for zero-gauge tenacity with the lower twist open-end spun yarn. They also stated that fiber length parameters were positively correlated with yarn tenacity. They found that correlation coefficients were nearly as large as that for fiber tenacity and yarn tenacity. Simpson and Murray [40] showed that fiber fineness was more important in open-end than in ring spinning due to poor fiber parallelization in open-end yarns and fiber strength was more important in ring spinning. They suggested that for the most efficient overall processing there must be a compromise between the fiber properties required for efficient carding and those for efficient spinning and end products. El Hattab *et al.* [41] also showed a positive correlation between fiber length and strength of yarn as for fiber properties/yarn strength relationships. Louis *et al.* [38] ranked fiber properties in their order of importance relative to yarn properties and end breakage in addition to ranking yarn properties in their order of importance relative to end breakage. They provided the result that fiber strength had a high coefficient with regard to yarn strength and low coefficient with end breakage. Also fairly high correlation coefficients were observed between fiber average stiffness with yarn strength, toughness with yarn elongation and fiber elongation with yarn elongation. He stated that fiber strength ranked first to yarn strength and fiber length to end breakage.

Tensile properties of single cotton fibers are susceptible to wide variations and poor replications between samples [42], and so a large number of specimens have to be tested [43]. Because single fiber data collection is tedious, time consuming, and

therefore expensive, the textile industry has for years relied on bundle tests to predict cotton performance [35]. Researchers also worked to develop methods to measure the bundle strength of cotton fibers [6]. Pressley published a paper on an instrument to test the strength of a flat bundle of fibers, which became known as the Pressley tester [7, 44]. In 1953, Hertel introduced the Stelometer for measuring the breaking force and elongation of flat fiber bundles [7, 45]. In 1960s, the U.S. Department of Agriculture and U.S. cotton producers began to support research to develop an automated "high speed" bundle strength tester, which resulted in the "high volume instrument (HVI)" system. Extensive studies have been made of each of these instruments to develop relationships between fiber bundle and yarn strength. Sasser *et al.* [7] showed, however, that correlations between fiber strength and yarn strength for the samples improved somewhat when they used the average single fiber strength rather than HVI or Stelometer bundle strength.

Despite the advantages of bundle testing, there has been a continuing need for improved testing methods and a better understanding of measurements made by existing methods [35]. Thibodeaux *et al.* [8] carried out the research about Mantis® single fiber tester to determine how its results could be made compatible with conventional bundle strength testers. They found a strong relationship between single fiber strength measurements and conventional bundle measurements and that the fiber fineness and maturity were useful in predicting the fiber strength. Deluca *et al.* [46] suggested that fiber fineness and other properties should be used for establishing model for determining broken fibers in yarns.

2.4 Changes of Various Properties of Cotton After Laundering

2.4.1 Morphology Characteristics of Cotton Fibers After Laundering

Several researchers made studies on the effects of moisture and heat on various cotton fiber properties [15, 23, 47-50]. Of many, the surface properties of cotton were found to play a very important role in determining the performance of the products and processes. In addition to contributing to yarn uniformity and mill efficiency, surface characteristics were shown to influence dye absorbency and reactivity rate as well as fabric feel, or handle [51]. Goynes and Rollins [52] studied untreated and chemically modified cotton fabrics which had been laboratory-abraded by machine-washing and tumble-drying with the scanning electron microscope. Young and Morris [53] compared abrasion caused by laundering-only with that caused by wear and laundering by SEM observation. They found that the cotton fibers were more damaged after repeated washing and drying thant polyester fibers. Buisson *et al.* [48] investigated abrasion and heat damage to desized and scoured cotton fabric during drying in a tumble dryer by means of SEM, weight, and tensile tests. The study addressed the moisture loss patterns of cotton fabric in a dryer and abrasion and heat damage from the drying process. They found out that the wet fabric tumbled with heat showed the highest weight increase and referred this phenomenon as the presence of moisture or shrinkage. They supported their conclusion by the strain tests where the wet fabric tumbled with heat also showed the highest peak strain.

2.4.2 Changes of Dimensional Properties of Cotton Fabrics After Laundering

Knitted fabrics are popular for their shape fitting properties, softer handle, bulkier nature, and high extension at low tension [54]. However, they also suffer from various forms of dimensional distortion due to the dimensional instability of knitted loop construction, especially after laundering steps. For elucidating the dimensional characteristics of knitted fabric, Munden [55] defined the relationship between courses per unit length, wales per unit length, and loop length using four parameters *k1, k2, k3, k4*:

$$k_1 = c \times w \times l^2$$
$$k_2 = c \times l$$
$$k_3 = w \times l$$
$$k_4 = c / w$$

where c = courses per unit length, w = wales per unit length and l = loop length. The significance of these equations is that plain knitted fabric dimensions are basically defined by the length of yarn in the knitted loop. All other variables, including knitting, yarn and machine variables only have effect on fabric dimensions with the change of loop length. Based on his theory, he then introduced the concept of a knitted fabric Cover Factor (CF) for plain-knit fabric quality control [56].

Postle [57] suggested the use of Tightness Factor (TF) as another means of fabric quality control. As shown on several researches [58-62], tightness factor influence the characteristics of single jersey fabrics. If the fabrics are measured basically in the same relaxed state, the fabric dimensional properties are

therefore predictable by applying the simple equations [63]. Wolfaardt [64] modified these equations in order to apply for the 1×1 Rib structure

There are two common dimensional changes occurring after laundering; a phenomenon called “spirality”, and fabric shrinkage. Spirality is shown as wales that are not perpendicular to courses. Several workers [65-67] have done the research about spirality and demonstrated that the most prominent factor causing spirality in a single-jersey fabric was the relaxation of torsional stresses in the yarn. Tao *et al.* [61] revealed the yarn twist factor and the fabric tightness factor promoted fabric spirality.

In 1939, Collins [68] introduced fundamental principles which govern the shrinkage of cotton goods by washing. He stated two key points of the problem; shrinkage does not occur unless water gains access to the material by one means or another, and the shrinkage can be ascribed to two causes; swelling and release of strains. He summarized that the shrinkage of cotton fabric could be analyzed into several portions. The largest amount of the shrinkage is that represented by increase of crimp; yarn shrinkage takes a second place, being generally much less than the increase of crimp, whilst fiber shrinkage is usually negligible. In 1967, Suh [69] suggested that the shrinkage of fabric is determined by fiber characteristics, stitch length, machine gauge, yarn twist. However, he addressed that swelling and deswelling of yarn are the most important factors responsible for the structural changes of the loop geometry of 1×1 plain knit during wet relaxation in washing and drying.

3 RESEARCH OBJECTIVES

The main objectives of this study are as follows:

1. Observe the changes in cotton quality in terms of the tensile properties of individual cotton fibers during textile processes and examine the effects of these processes on the tensile properties
2. Investigate the effects of ginning and carding rates on the tensile properties of single cotton fibers as well as on the shrinkage of the washed garments after repeated washing and drying.
3. Establish a comprehensive model for explaining the tensile performance of single cotton fibers based on their cellular microstructure as bicomponent bundle.
4. Investigate the relationship between the dimensional stability of garments undergone repeated washing/drying and the effects of ginning and carding rates.

4 EXPERIMENTS

In order to investigate the effects of textile processes on the tensile properties of cotton fibers from the harvesting to consuming of end-products, it was necessary to collect, process, and test considerable amount of fibers. Although HVI data or AFIS data have provided us varieties of properties of cotton, they have limited amount of usages. Furthermore, these data could be obtained beyond carding process. Therefore, it is not possible to study the changes by HVI or AFIS in a roving, yarn or fabric form. In addition, the HVI tests represent bundle properties in lieu of single fiber tensile properties.

Three varieties of cotton grown in the region of Stoneville and Deltapine, MS. were selected for the research. Cotton samples from Stoneville 747 (STV 747), Stoneville 4892 (STV 4892), and Deltapine 33B (DPL 33B) were provided by the USDA Ginning Laboratory in Stoneville, MS. The cotton samples were ginned by hand, and by machine with various ginning conditions at USDA Stoneville Ginning Laboratory. The ginned cottons were transferred to USDA-ARS Laboratory at Clemson for Carding, Spinning, and Knitting. Cotton fibers with various carding conditions were collected right after carding and tested by Mantis® single fiber.

As reference data, the AFIS and HVI data of the fiber samples were obtained in each processing stage at USDA-ARS Clemson Lab, and the official HVI data at USDA-AMS, in Memphis, TN.

Knitted fabrics were finished and scoured in Cotton Incorporated™, and then made into 1×1 plain T-shirts at $[TC]^2$ for the subsequent repeated washing and drying experiment. The T-shirts were subjected to 32 cycles of repeated washing and drying at

Cotton Incorporated. Progressive shrinkages were measured in the length and width directions of the T-shirts. At the end of the 32 cycles, the cotton fibers were pulled out from the T-shirts and tested with Mantis® for measuring their tensile properties. The followings provide a detailed description of the experimental procedures.

4.1 Sing Fiber Tensile Test by Mantis®

Individual cotton fibers obtained from raw cotton, ginned cotton, card slivers, unwashed T-shirts and washed T-shirts were tested by Mantis® single fiber tensile tester. Initial gauge length of two grabbing jaws of the tester is 3.175mm. It is constant rate of extension (CRE) type tester and the jaw movement rate is 1.00 mm/sec. This tensile tester is much faster than conventional Instron® or other tensile tester. Due to large variations in the properties of natural cotton fiber, a great amount of time and labor should be required for the large number of tests.

4.2 Hand-picked and Hand-ginned Cotton

Two out of Three cotton varieties (STV 747 and STV 4892) were selected and harvested at the cotton field by hand. Seed cottons collected from a cotton plant were picked by hand, and seeds and trashes were taken and removed also by hand. To obtain more representative samples for the field, bolls were picked randomly and mixed thoroughly by a blending machine. After hand-picking and hand-ginning, the fiber samples were tested by Mantis® single fiber tester.

4.3 Spindle-harvested and Conventional Ginning Process

The tensile properties of these samples are to be compared with that of the spindle-harvested and machine-ginned samples.

Cotton samples were processed with two different ginning rates (75% and 125% of the capacity). The rates were obtained by adjusting the throughput of the cotton in the gin. During ginning, cotton was processed with lint cleaners. Although two lint cleaners are used in general, we processed cotton in tow ways; one sample run through one lint cleaner and the other through two lint cleaners. Moisture content was adjusted by controlling the temperature in the drier. A higher drying temperature leaves less moisture in cotton fiber. Drying temperatures were set roughly at 100ºF and 200ºF, and the ginning was replicated at each level to increase the precision of the estimated effects and enable us to estimate the interaction effects. The breaking elongation, breaking strength, and breaking energy were measured using a Mantis® for each combination.

4.4 Experimental Design for Ginning and Carding Effects – Based on Card Slivers

With the hand-processed cotton representing the base-line of the cotton quality, ginning was done at two ginning rates, 75% and 125% of the normal ginning rate by roler gin. It is obtained by adjusting the throughput of the cottons. At each ginning rate, the samples were processed with both one and two lint cleaners.

Following ginning, the cotton samples were shipped for carding. Ginned cotton bales were opened by hand and put into the “blend hopper” consisting of three

hoppers and then transferred to “AXI-FLO AFC,” a double-roll cleaner. Following these processes, cottons were blended and cleaned in “GBRA,” another blending machine. Through a coarse cleaner called “RN” with 18” roller with 3” spikes, cottons were cleaned. A further cleaning was done in “RST,” a fine cleaner. Dust was removed from cottons by DUSTEX™. Finally, the cotton samples were processed in a DK 740 card to produce 70 grain card slivers.

Carding rates applied in this experiment were 60 lbs./hour and 120 lbs./hour. These were relatively lower and higher rates than the commercial carding rate of 100 lbs./hour. The carding machine (Truetzchler DK740) used in this research had 1 licker-in roller. Wastes from this process were tested on a Shirley Analyzer. In addition, evenness tests and AFIS fiber length tests were performed on each card sliver.

Table 1 shows the experimental design for obtaining the effects of ginning and carding rates and the number of lint cleaners.

Table 1. Experimental Design for Producing Samples – Card Slivers

Sample ID	Ginning Rate (% of capacity)	No. of Lint Cleaner	Carding Rate (lbs./hr)	Lot Number
STV 747	75	1	60	30
			120	40
		2	60	41
			120	44
	125	1	60	7
			120	11
		2	60	15
			120	27
DPL 33B	75	1	60	33
			120	43
		2	60	45
			120	48
	125	1	60	3
			120	5
		2	60	29
			120	46

4.5 Drawing, Spinning and Knitting

After carding, card slivers were drawn in a RS 951 draw frame without autoleveler and then a RS 351 with autoleveler. Then, the slivers were processed into rovings with 0.75 hanks and 1.30 TM. The rovings weighing roughly one pound were spun into ring-spun yarns by a Zinser 321 frame. The machine had maximum spinning rate of 21m/min. All rovings were spun into 20/1 Ne yarn at 14,000 spindle speed with 3.85 TM.

Subsequently, the ring spun yarns were knitted into plain jersey fabrics by a Vanguard Supreme circular knitting machine. The fabrics were sent to Cotton Incorporated for scouring and finishing in two fabric rolls.

4.6 Garment Manufacturing

The knitted fabrics matching different treatment combinations were sent to $[TC]^{2®}$ for T-shirts production. The T-shirts were sewn with side seams in order to produce medium sizes. The T-shirts were with short sleeves with 1" serged hems at the sleeves and at the garment bottoms. In addition, a 1x 1 rib knit fabrics were used for producing necks.

4.7 Repeated Washing and Drying of T-shirts

Experiments were designed to observe the progressive shrinkages and other dimensional changes and to study their relationships with the single fiber tensile properties matching the ginning and carding conditions. The experimental scheme includes repeated washing/drying, measurement of dimensional changes, and testing of single fiber tensile properties.

The laundering and drying experiments were carried out by using AATCC Test Method 150-1995 [84]. This test method was for determining dimensional changes of garments by placing bench marks on designated areas of the garments [85].

4.7.1 Apparatus and Materials

An automatic commercial washer and tumble-dryer were employed for the tests as prescribed by the AATCC method.

4.7.2 Specimens

Each garment was considered as a specimen. Three specimens of each type were tested in order to increase the precision of the average. Prior to the tests, pre-conditioning was done as required by ASTM D 1776. T-shirt samples were placed separately under the standard condition (21 ± 1°C and 65 ± 2% RH) for at least 4 hours. For measuring dimensional changes, we placed bench marks on the surface of the garments. The locations of bench marks in T-shirt were in collars, collar bands, body lengths, sleeve lengths, and cuffs. Among these locations, we chose collar bands, body lengths, and sleeve lengths. The distance between bench marks was determined by the size of the T-shirt. The measurements were recorded to the nearest millimeter values or tenth of an inch, and the % change was computed based on the initial dimensions.

4.7.3 Test Procedure

The washing and drying conditions and the settings are summarized as follows. In order to eliminate the possible effects from different washers and dryers, one washer and one dryer were used. After filling specified volume of water, 16 T-shirt samples were put into the washer. Each washing and drying load was 6.2 lbs. and the washing was performed without ballast. The washing and drying conditions for the AATCC test method are shown in Tables 2-4. In this study, the normal machine cycle, water temperature of 120 ± 5F^{o}, and tumble drying (normal) cycle were used. Each washing cycle was 30 minutes with the rinse temperature set at 85°F. The test specimens were transferred to the

dryer immediately after the final washing cycle. The washed garments were placed in the tumble dryer with the temperature settings for cotton garments as described in Table 2. For each group of T-shirts, a total of 32 cycles of washing/drying were completed. The 32 cycles of washing/drying were chosen because the progressing shrinkages became minimal at that point.

At the completion of washing and drying cycles, the specimens were conditioned under the standard atmosphere, namely, 21 ± 1°C (70 ± 2°F) and 65 ± 2% RH for 4 hours.

4.7.4 Measurements

Figure 2 shows the positions measured for dimensions of T-shirts. The distance between each pair of bench marks were measured and recorded to the nearest millimeter, or to the nearest tenth of an inch or smaller increment.

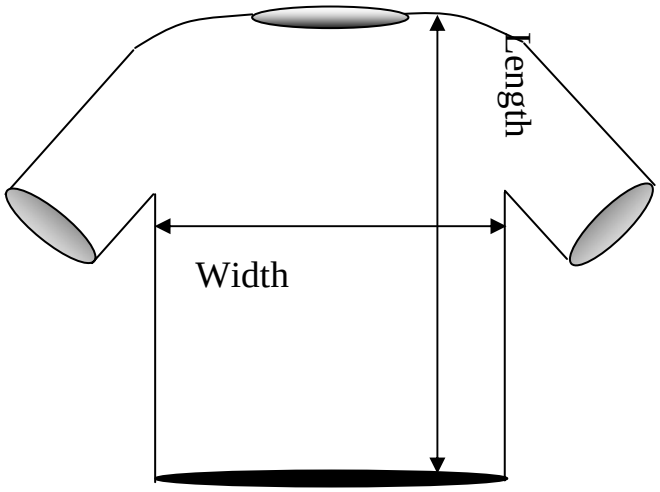

Figure 2. Measurements in a T-shirt

4.7.5 Calculation and Interpretation

The dimensional changes in T-shirt samples were calculated as % changes of original dimensions following a pre-designated number of washing and drying cycles as follows:

$$\%DC = 100(A - B) / A \tag{7}$$

where:

DC = Dimensional change

A = Original dimension

B = Dimension after laundering

Table 2. Washing and Drying Conditions

Machine Cycle	Washing Temperatures	Dryer Procedures
(1) Normal/Cotton Sturdy	(II) 27 ± 3°C (80 ± 5°F)	Tumble: i. Cotton Sturdy ii. Delicate iii. Permanent Press
(2) Delicate	(III) 41 ± 3°C (105 ± 5°F)	(B) Line
(3) Permanent Press	(IV) 49 ± 3°C (120 ± 5°F)	(C) Drip
	(V) 60 ± 3°C (140 ± 5°F)	(D) Screen

Table 3. Washing Machine Setting Conditions without Load

	Normal	Delicate	Permanent Press
(A) Water Level	18 ± 1 gal	18 ± 1 gal	18 ± 1 gal
(B) Agitator Speed	179 ± 2 spm	119 ± 2 spm	179 ± 2 spm
(C) Washing Time	12 min.	8 min.	10 min.
(D) Spin Speed	645 ± 15 rpm	430 ± 15 rpm	430 ± 15 rpm
(E) Final Spin Cycle	6 min.	4 min.	4 min.

Table 4. Dryer Setting Conditions

	Cotton Sturdy	Delicate	Permanent Press
Exhaust Temperature	High 66 ± 5°C (150 ± 10°F)	Low < 60°C (140°F)	High 66 ± 5°C (150 ± 10°F)
Cool Down Time	10 min.	10 min.	10 min.

4.8 Microscopic Observation

Surface properties of cotton play an important role in textile products and processes. In addition to contributing to yarn uniformity and mill efficiency, surface characteristics influence dye absorbency and reactivity rate as well as the fabric handle. In this study, efforts were made to examine the possible effects of ginning and carding conditions on the surface properties of cotton fibers through a scanning electron microscope at NCSU. Any degradation in tensile properties of cotton fibers could also be manifested by the optical properties of cotton fiber surfaces.

4.8.1 Apparatus

Hitachi S-3200 variable pressure scanning electron microscope (ESEM) was used for the optical experiment.

4.8.2 Materials

Three T-shirts representing high, normal, and low shrinkages were selected based on the results of the 32 cycles of repeated washing/drying tests. Samples were cut in sizes of 0.5 × 0.5 mm from the three T-shirts and placed on the mount and coated with gold by the sputter coater.

5 RESULTS AND DISCUSSIONS

5.1 Comparative Study on the Effects of Ginning Methods on Tensile Properties of Ginned Cotton: Hand Ginning vs. Machine Ginning

Although it seems obvious that cotton processing by machine would give more damage than that processed by hand, a direct comparison between these two methods provide general ideas as to whether the hypothesis is true. For this reason, we initiated this study by comparing the two ginning methods in terms of the tensile properties of the cotton ginned. First, we obtained three groups of cotton fiber samples from STV 747, which were taken at the end of three different ginning rates; *high*, *normal*, and *low*. High, normal, and low ginning rates represent 125%, 100%, and 75% of the conventional ginning rate, respectively. The ginning rates were altered by changing the ginning speed. A total of 4,800 single fibers were tested for the samples taken at the three ginning rates by comparing them with the three sets of tensile data obtained from the 3 ginning rates. An in-depth study was made on the hand-ginned cottons from three varieties. Details of the experiment are as follows; three varieties of cotton grown in the region of Stoneville and Deltapine, MS. were selected. They were cotton samples from Stoneville 747 (STV 747), Stoneville 4892 (STV 4892), and Deltapine 33B (DPL 33B) provided by the USDA Ginning Laboratory in Stoneville, MS. Hand-picked and hand-ginned cotton fibers are assumed to have retained the original fiber qualities by assuming that the damages were kept at a minimum level. The tensile properties of cotton fibers thus obtained

have been compared against that of the spindle-harvested and machine-ginned cottons.

5.1.1 Effects of Ginning Rates on Tensile Properties of Ginned Cotton Fibers

The results of Mantis® single fiber tensile tests are summarized in Table 5. The average breaking strength, breaking elongation, and work to break are shown along with their standard deviation and range.

Table 5. Summary Statistics of Tensile Properties of Ginned Cotton Fibers Processed with Three Ginning Rates (No. of Sample Tested: 4800)

		High Rate	Normal Rate	Low Rate
Sample Size		1600	1600	1600
Breaking Strength (gf)	Mean	5.92	5.91	5.56
	Std. Dev.	2.36	2.41	2.26
	Min.	0.47	0.31	0.47
	Max.	14.94	15.34	14.56
Breaking Elongation (%)	Mean	16.98	16.89	19.20
	Std. Dev.	6.97	6.86	7.50
	Min.	0.04	0.14	0.07
	Max.	43.47	54.24	47.97
Breaking Energy (μJ)	Mean	16.48	16.65	17.28
	Std. Dev.	9.94	10.30	9.97
	Min.	0	0.01	0.01
	Max.	80.38	67.20	66.21

For cotton fibers ginned at high rates, the average breaking elongation and the average breaking strength were 16.98% and 5.92gf, respectively, while the same at low ginning rate were 19.20% and 5.56gf. The differences suggest that cotton fibers processed at a higher ginning rate produced a lower mean the

breaking elongation than that processed at a lower ginning rate. However, the fibers were shown to have a higher mean breaking strength when they were ginned at a higher ginning rate than that at the normal and low ginning rates. Based on this, it is clear that the higher fiber extension associated with the high-speed ginning might have reduced the breaking elongation as a result of unrecovered elongation at the end of ginning. For the breaking strength, the higher ginning rate seemed to have enhanced the average strength compared to that from the low ginning rate. In examining the results from the “normal” rate, however, there was no reduction of breaking elongation compare to that from the “low” rate. This could mean that a threshold in fiber extension exists matching the ginning rate and a significant reduction of breaking elongation may occur if the ginning rate exceeds the threshold limit.

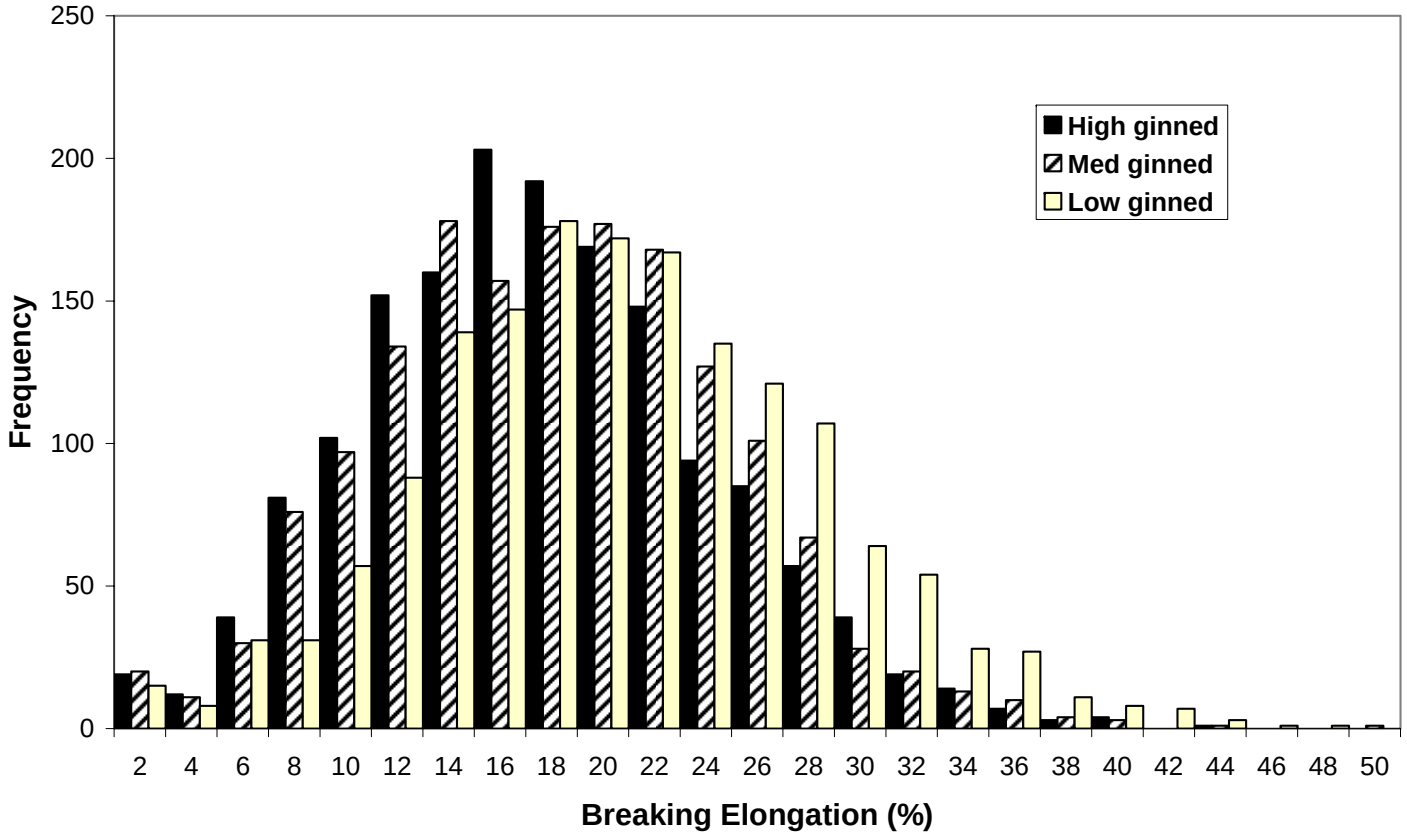

Figure 3. Distributions of Breaking Elongation of Ginned Cottons for Different Ginning Rates (No. of test: 4800)

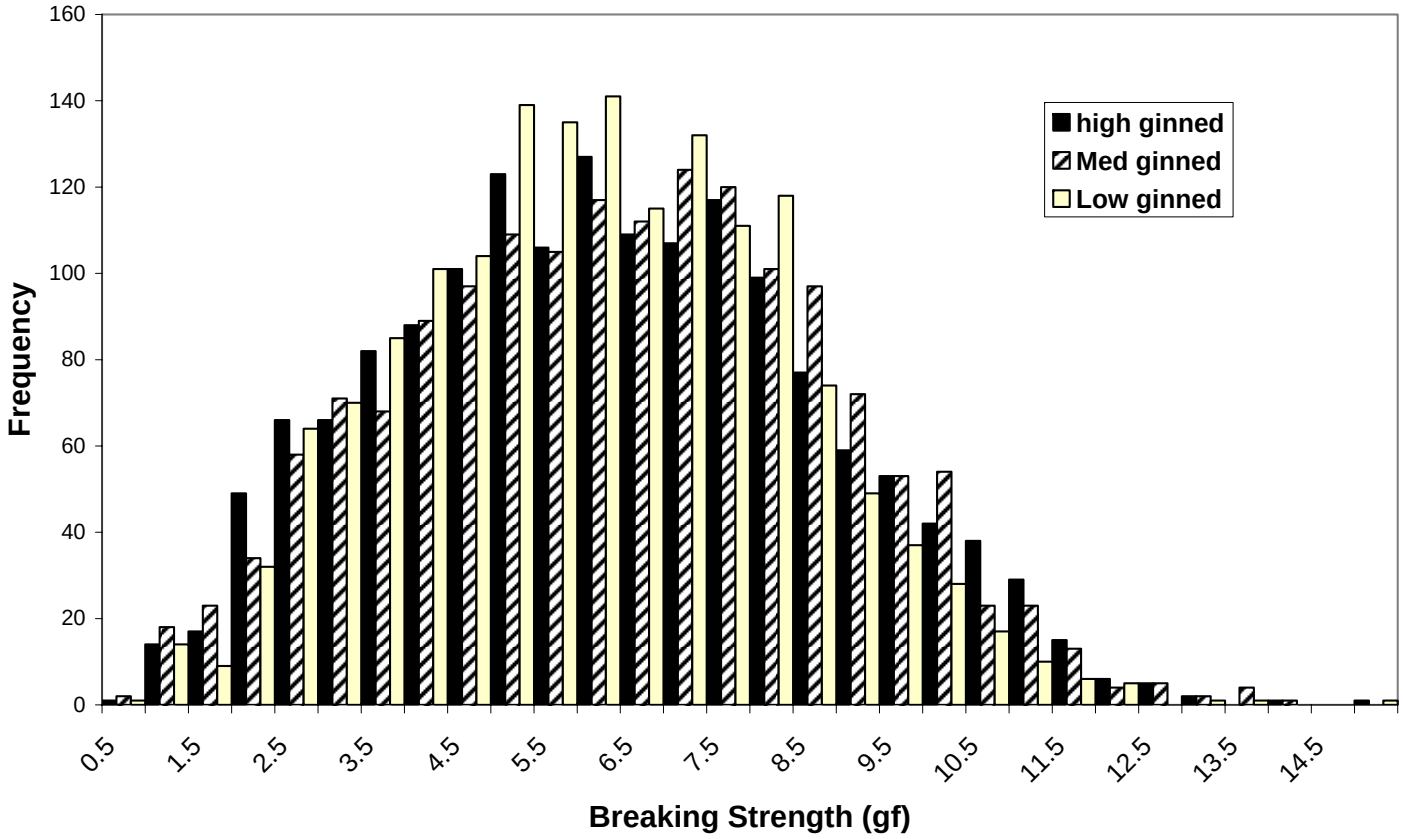

Figure 4. Distributions of Breaking Strength of Ginned Cottons for Different Ginning Rates (No. of test: 4800)

Figure 3 and Figure 4 show the distributions of the breaking elongations and the breaking strengths, respectively, of cottons processed at three ginning rates. These histograms clearly show that the higher ginning rate resulted in a decrease in the breaking elongation and an increase in the breaking strength compared to the lower ginning rate. Except the change of averages at the high ginning rate, the distributional features do not seem to have changed as a result of the changes in the ginning rate. These distributions are shown to be symmetric and normal in shape. In Figures 5- 7, the breaking strength (Y) and the breaking elongation (X) of two out of three fiber samples ginned at different rates were plotted. In comparing the high and normal rates, the breakage points were plotted (Figure 5) simultaneously in one graph. The differences, however, between the two were not obvious. Figures 6 and 7 show comparisons of high vs. low and normal vs. low, respectively. From these scatter plots, the breaking elongations of cotton from low ginning speed seemed to be greater than that from the other rates. That is, the cotton samples ginned at the low rate exhibited higher breaking elongations than that from the normal and high ginning rates. Unlike the cases for breaking elongation, the breaking strength showed different responses to the different ginning rates. The high ginning rate resulted in a higher average breaking strength whereas the fibers ginned at the low rate produced a low average breaking strength. This phenomenon will be analyzed and discussed in later sections in detail.

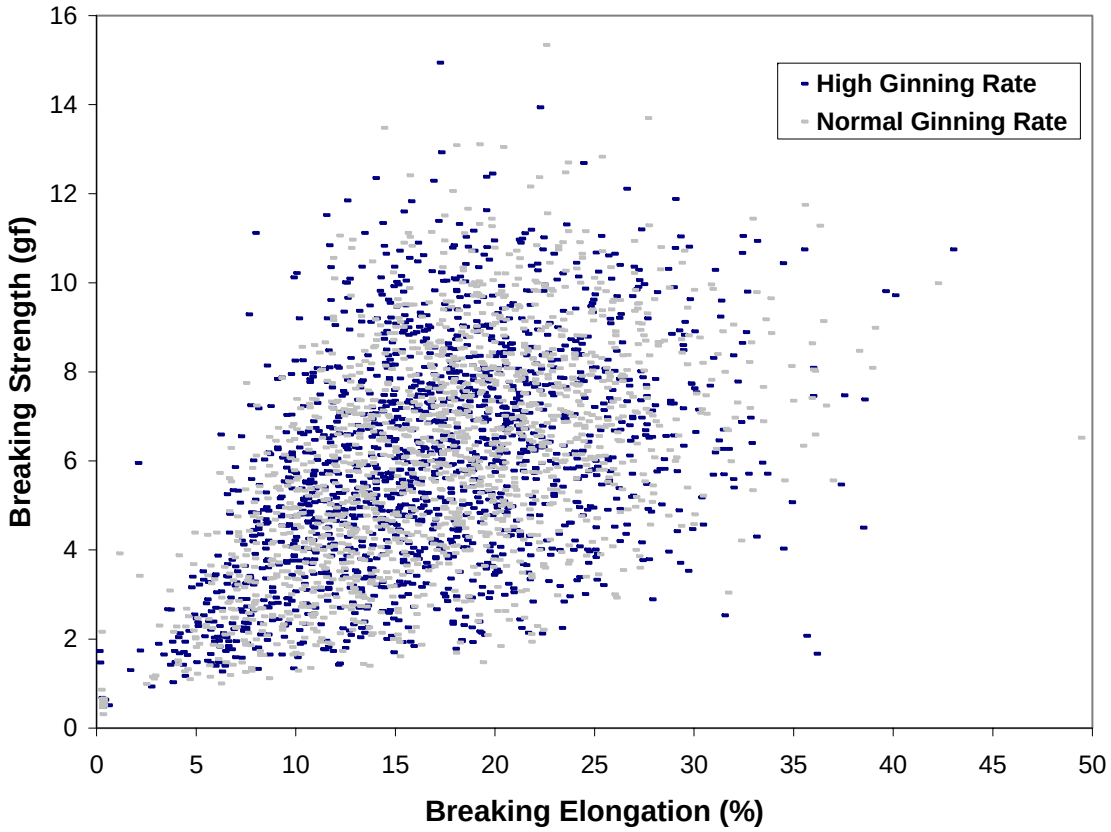

Figure 5. Scatter Plot of Breaking Strength vs. Breaking Elongation of Single Fibers: High Ginning Rate vs. Normal Ginning Rate (No. of test: 3200)

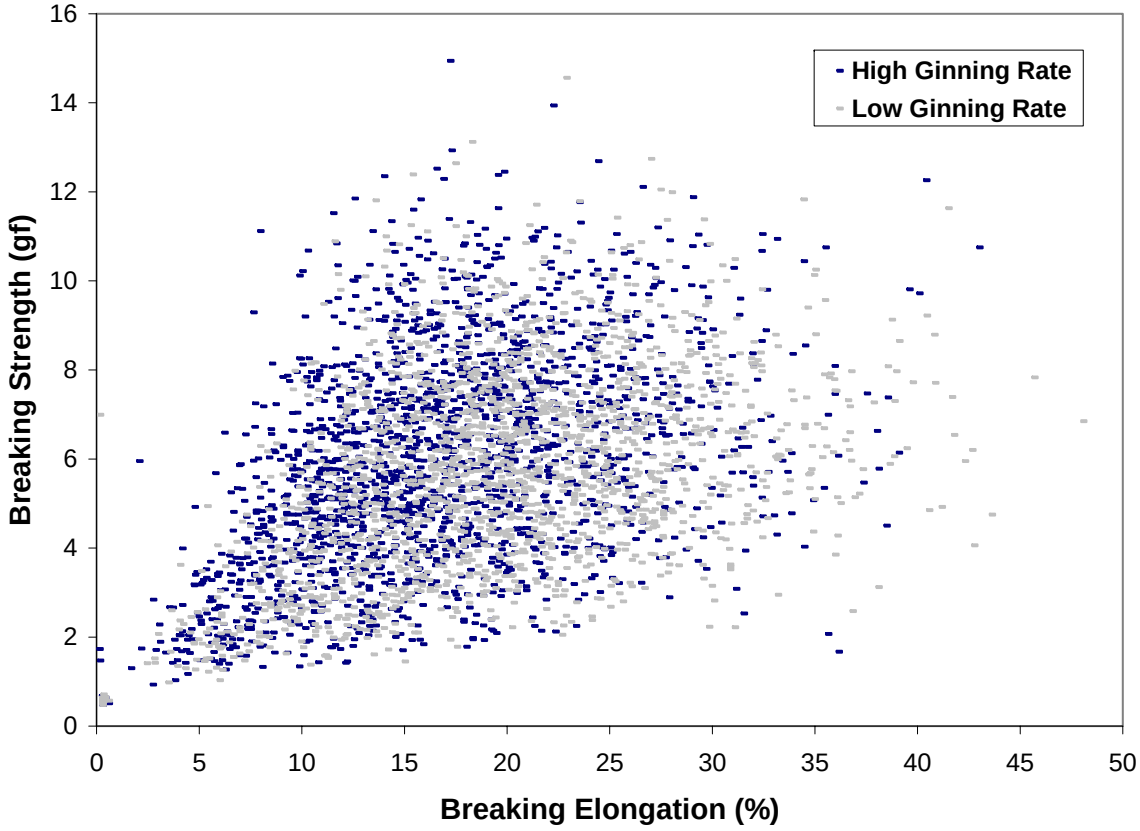

Figure 6. Scatter Plot of Breaking Strength vs. Breaking Elongation of Single Fibers: High Ginning Rate vs. Low Ginning Rate (No. of test: 3200)

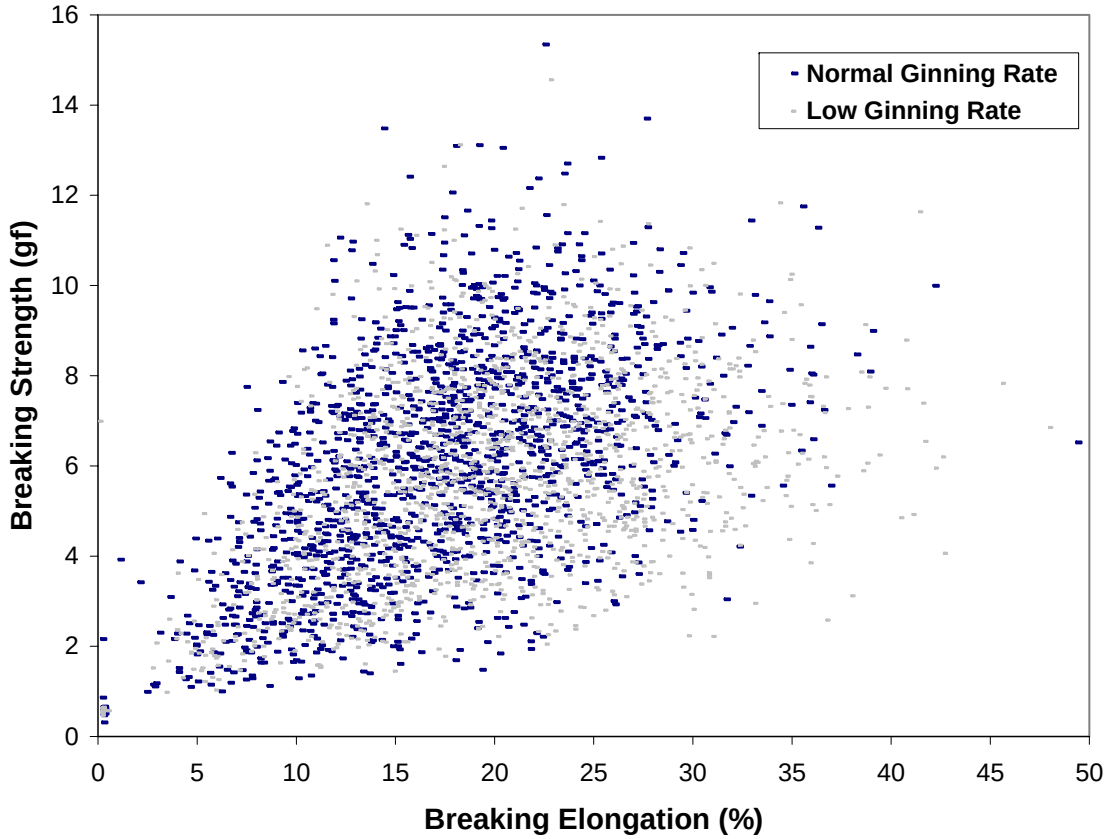

Figure 7. Scatter Plot of Breaking Strength vs. Breaking Elongation of Single Fibers: Normal Ginning Rate vs. Low Ginning Rate (No. of test: 3200)

5.1.2 Comparison of the Tensile Properties for Hand-ginned Cotton and Machine-ginned Cotton

Although it seems to be obvious that the picking cotton balls and ginning by hand would impart less damage to cotton fibers, the proof has never been established based on single fiber tensile tests. Based on Table 6, the hand-picked/hand-ginned cotton showed the highest breaking elongation and breaking strength, and the differences from all three mechanical ginning rates were found to be statistically significant. While the sample sizes are rather small and no replicate tests were performed, the results provide a strong evidence that the mechanical impacts on fibers generated by machine ginning indeed lowered the breaking strength, breaking elongation and the work to break at all ginning rates.

Table 6. Summary Statistics for Single Fiber Tensile Properties - Obtained at Three Different Ginning Rates and from Hand-ginned Cotton

		High Ginning Rates	Normal Ginning Rates	Low Ginning Rates	Hand-ginned
Sample Size		2399	1999	2400	800
Breaking Strength (gf)	Mean	5.92	5.91	5.56	6.36
	Std. Dev.	2.36	2.41	2.26	2.13
	Min.	0.47	0.31	0.47	0.76
	Max.	14.94	15.34	14.56	15.04
Breaking Elongation (%)	Mean	16.98	16.89	19.20	21.11
	Std. Dev.	6.97	6.86	7.50	7.24
	Min.	0.04	0.14	0.07	0.33
	Max.	43.47	54.24	47.97	49.41
Work done During Test (μJ)	Mean	16.48	16.65	17.28	20.29
	Std. Dev.	9.94	10.30	9.97	9.85
	Min.	0	0.01	0.01	0.06
	Max.	80.38	67.20	66.21	62.66

5.1.3 Hand-picked and Hand-ginned Cottons

We selected three varieties of cotton grown in the Stoneville region and Deltapine, MS. Cotton samples from Stoneville 747 (STV 747), Stoneville 4892 (STV 4892), and Deltapine 33B (DPL 33B) were provided by the USDA Ginning Laboratory in Stoneville, MS. Cotton fibers picked and ginned by hand are assumed to retain the original fiber qualities with damages kept at a minimum level.

Table 7. Summary Statistics of Tensile Properties of DPL 33B Hand-ginned Cotton (No. of sample tested: 4400)

	Breaking Strengths	Breaking Elongations
Mean	5.63	16.95
Std Err	0.04	0.09
Median	5.41	16.49
Mode	3.52	15.49
Std. Dev.	2.40	5.79
Sample Variance	5.77	33.51
Kurtosis	-0.36	0.45
Skewness	0.42	0.49
Range	13.59	47.49
Minimum	0.51	-0.20
Maximum	14.10	47.29
Count	4400.00	4400.00

Table 8. Summary Statistics of Tensile Properties of STV 747 Hand-ginned Cotton Fibers (No. of sample tested: 4400)

	Breaking Strengths	Breaking Elongations
Mean	6.90	20.65
Std Err	0.04	0.11
Median	6.92	20.18
Mode	7.17	21.45
Std. Dev.	2.41	7.25
Sample Variance	5.82	52.51
Kurtosis	0.13	0.32
Skewness	0.18	0.48
Range	19.36	47.50
Minimum	0.47	0.04
Maximum	19.83	47.54
Count	4400.00	4400.00

Table 9. Summary Statistics of Tensile Properties of STV 4892 Hand-ginned Cotton Fibers (No. of sample tested: 4400)

	Breaking Strengths	Breaking Elongations
Mean	5.62	16.03
Std Err	0.03	0.08
Median	5.38	15.53
Mode	5.92	16.13
Std. Dev.	2.23	5.02
Sample Variance	4.96	25.22
Kurtosis	0.88	0.35
Skewness	0.69	0.54
Range	18.20	34.65
Minimum	0.52	-0.16
Maximum	18.72	34.49
Count	4400.00	4400.00

Tables 7-9 show the summaries of single fiber tensile properties of hand-picked and hand-ginned cotton. The data are plotted in Figures 8- 13. For STV 4892 and DPL 33B, there were little differences in their breaking strengths and breaking elongations. For STV 747, however, there were noticeable differences in the tensile properties.

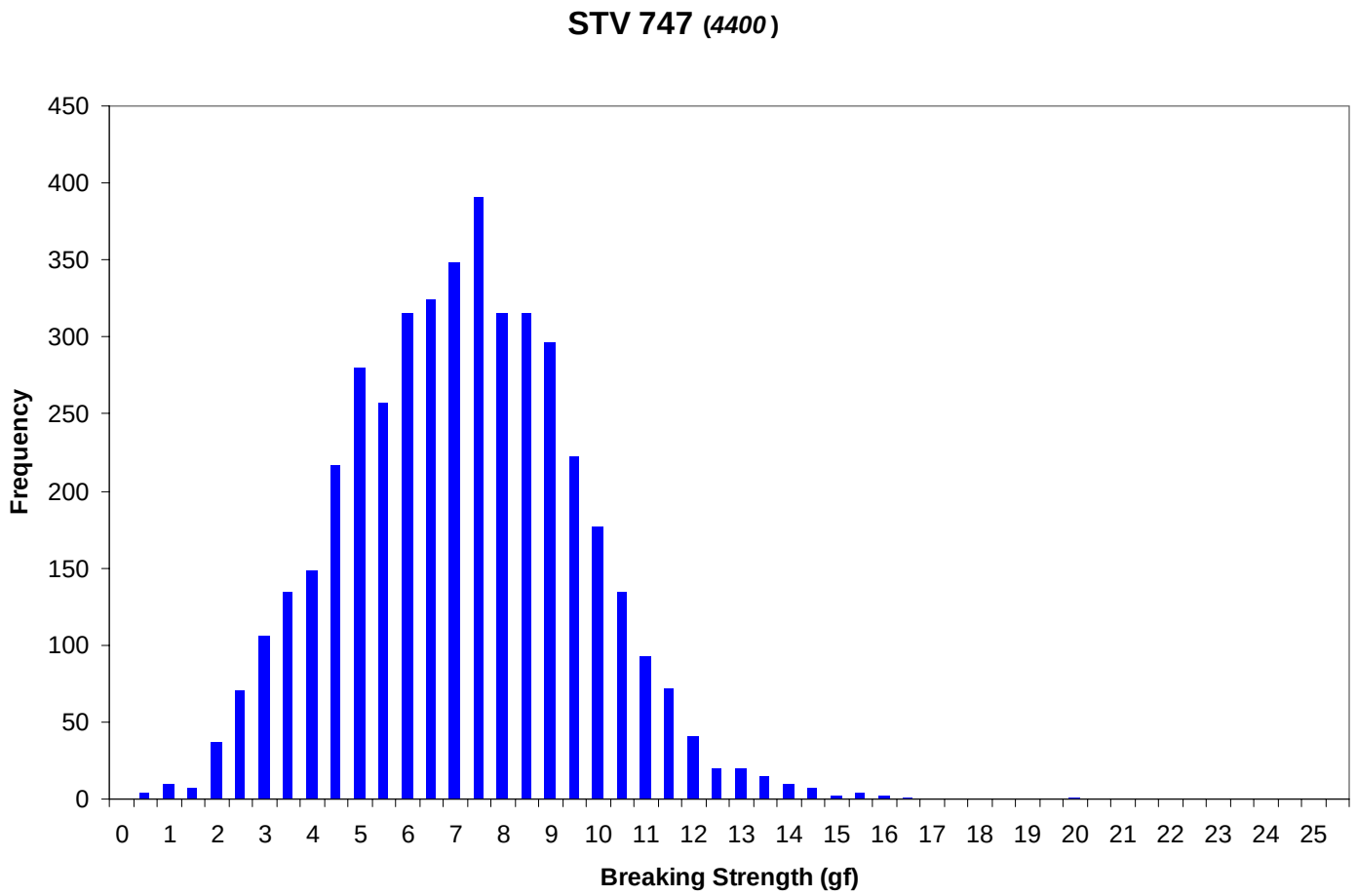

Figure 8. Histogram of Single Fiber Strength for STV 747 (No. of test: 4400)

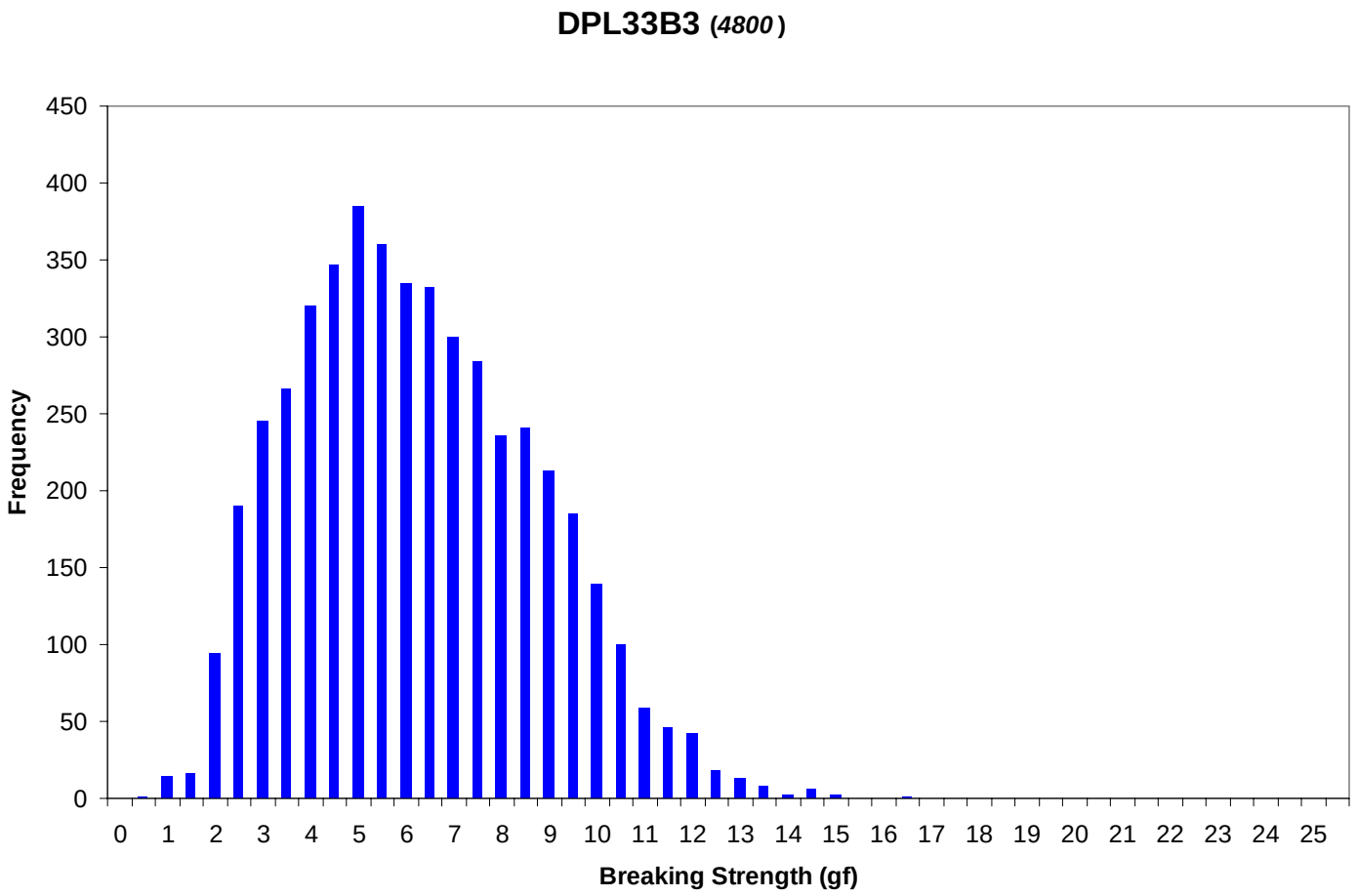

Figure 9. Histogram of Single Fiber Strength for DPL 33B (No. of test: 4800)

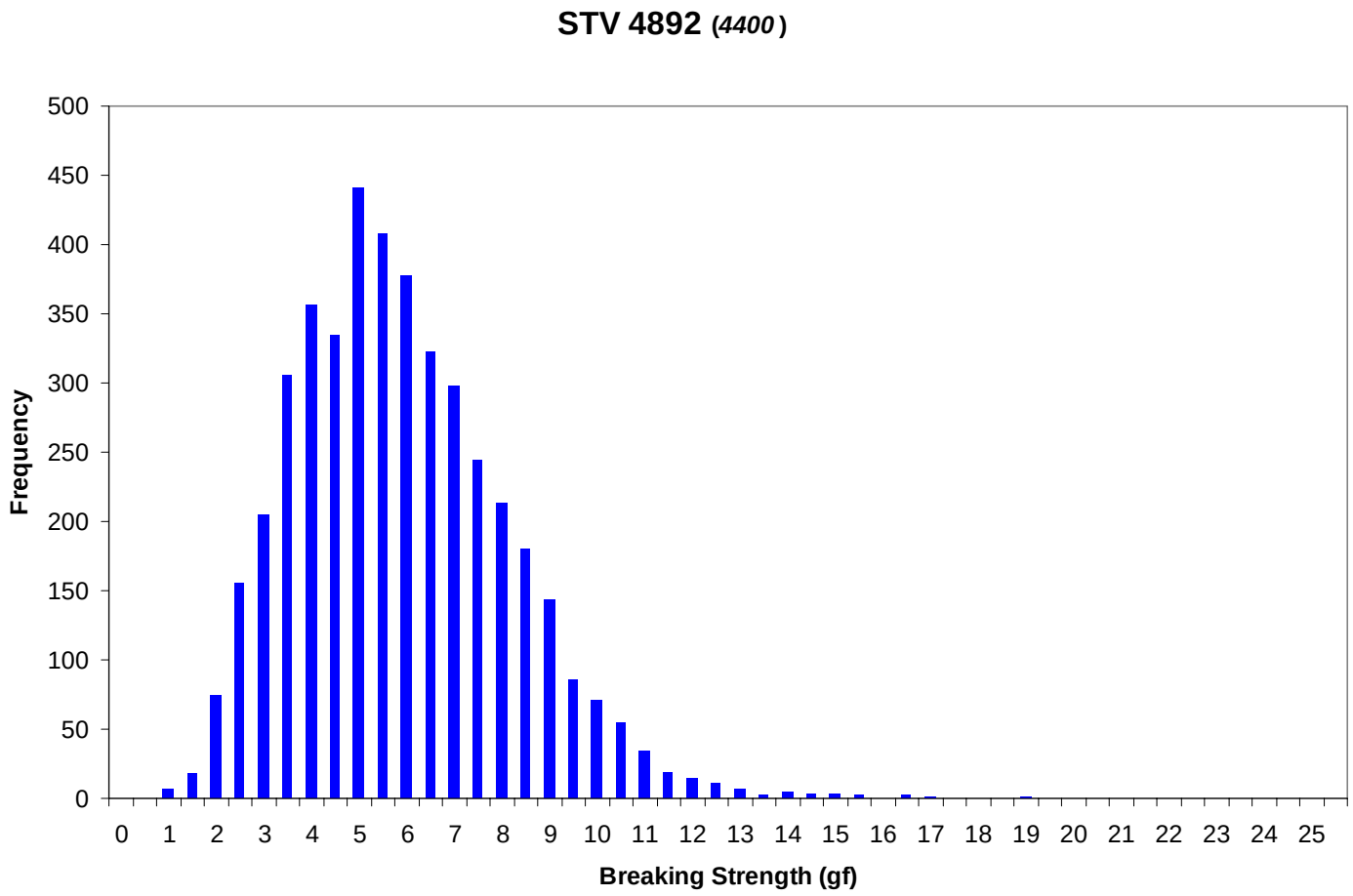

Figure 10. Histogram of Single Fiber Strength for STV 4892 (No. of test: 4400)

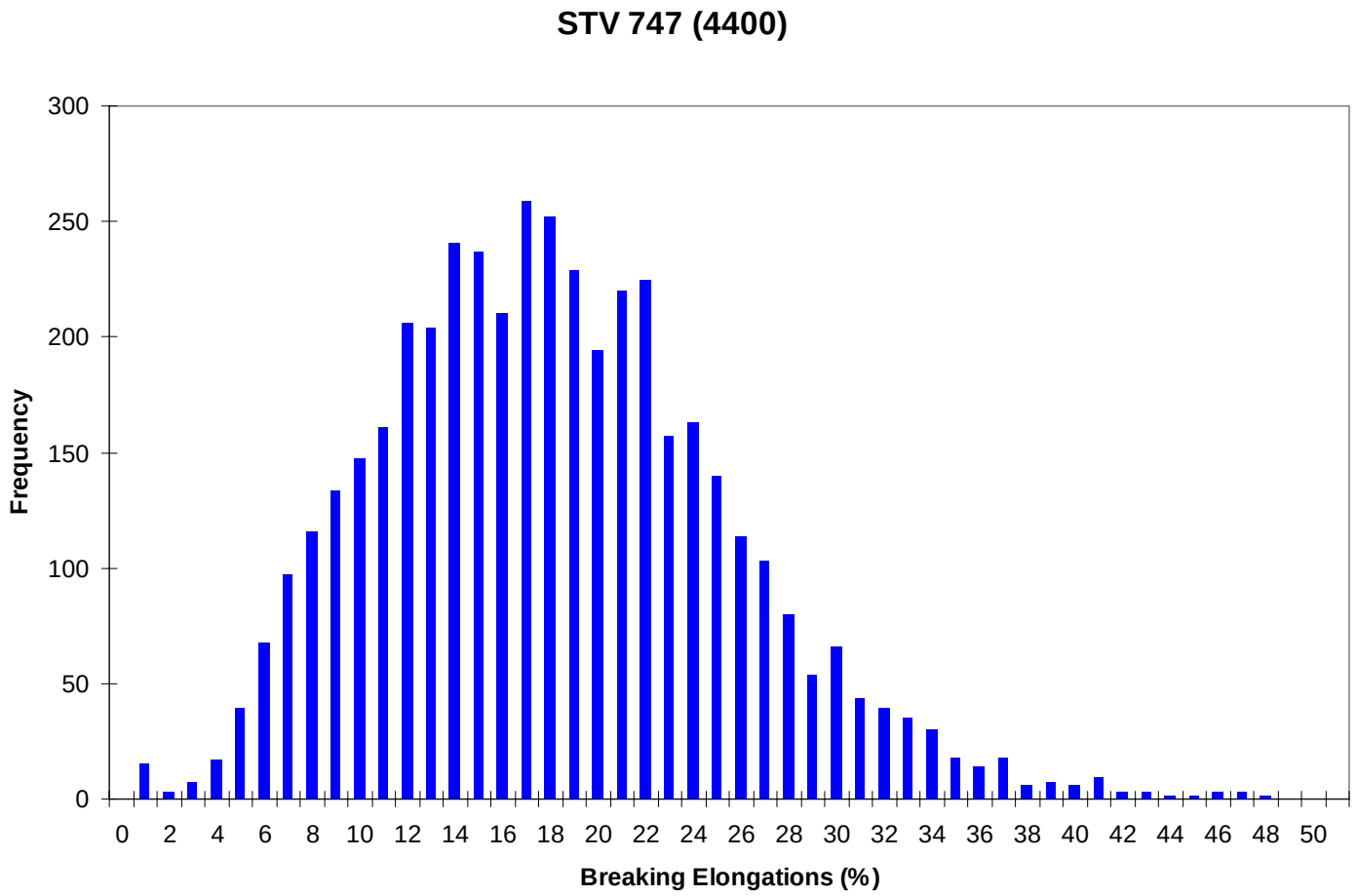

Figure 11. Histogram of Single Fiber Elongation for STV 747 (No. of test: 4400)

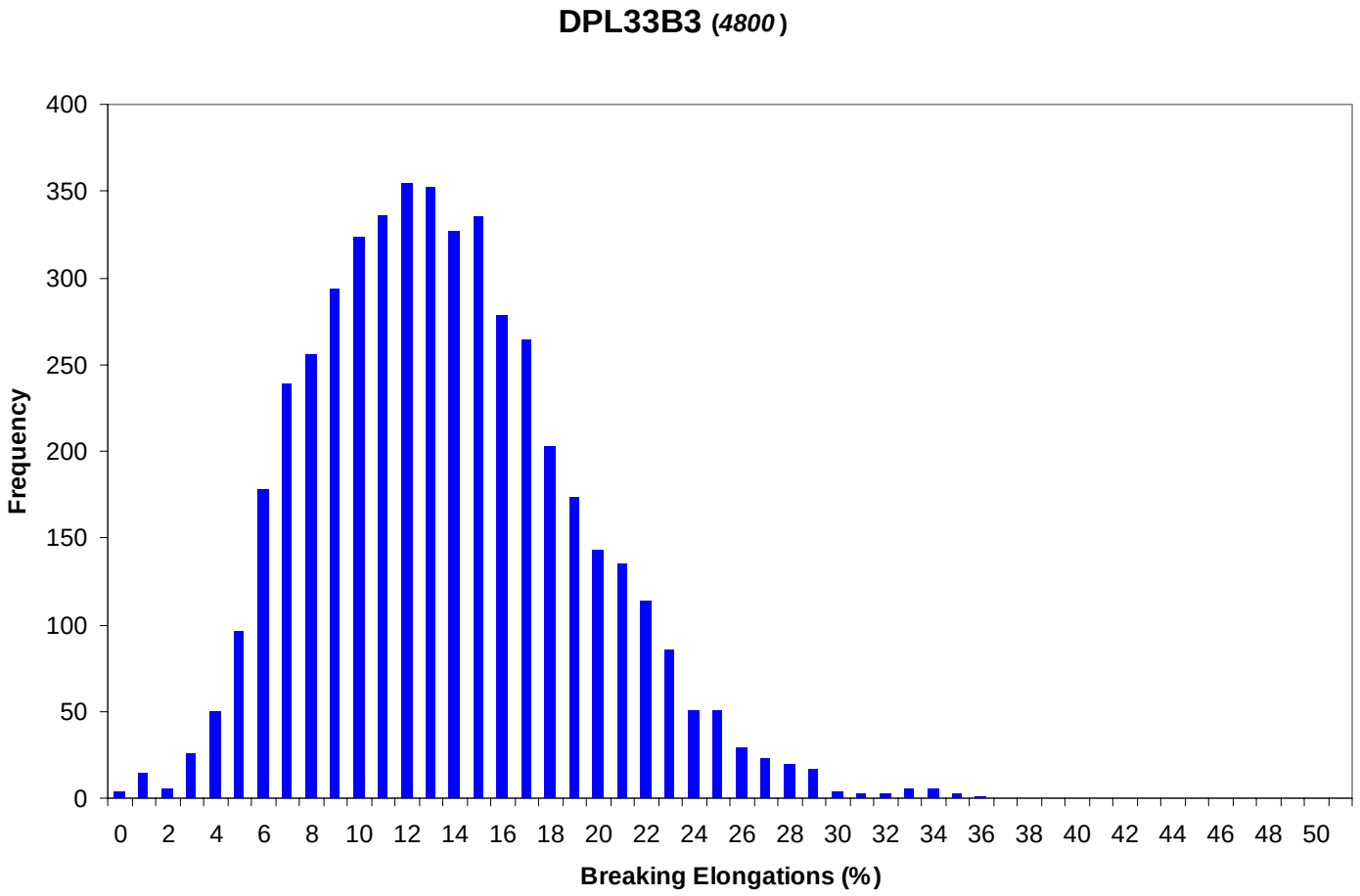

Figure 12. Histogram of Single Fiber Elongation for DPL 33B (No. of test: 4800)

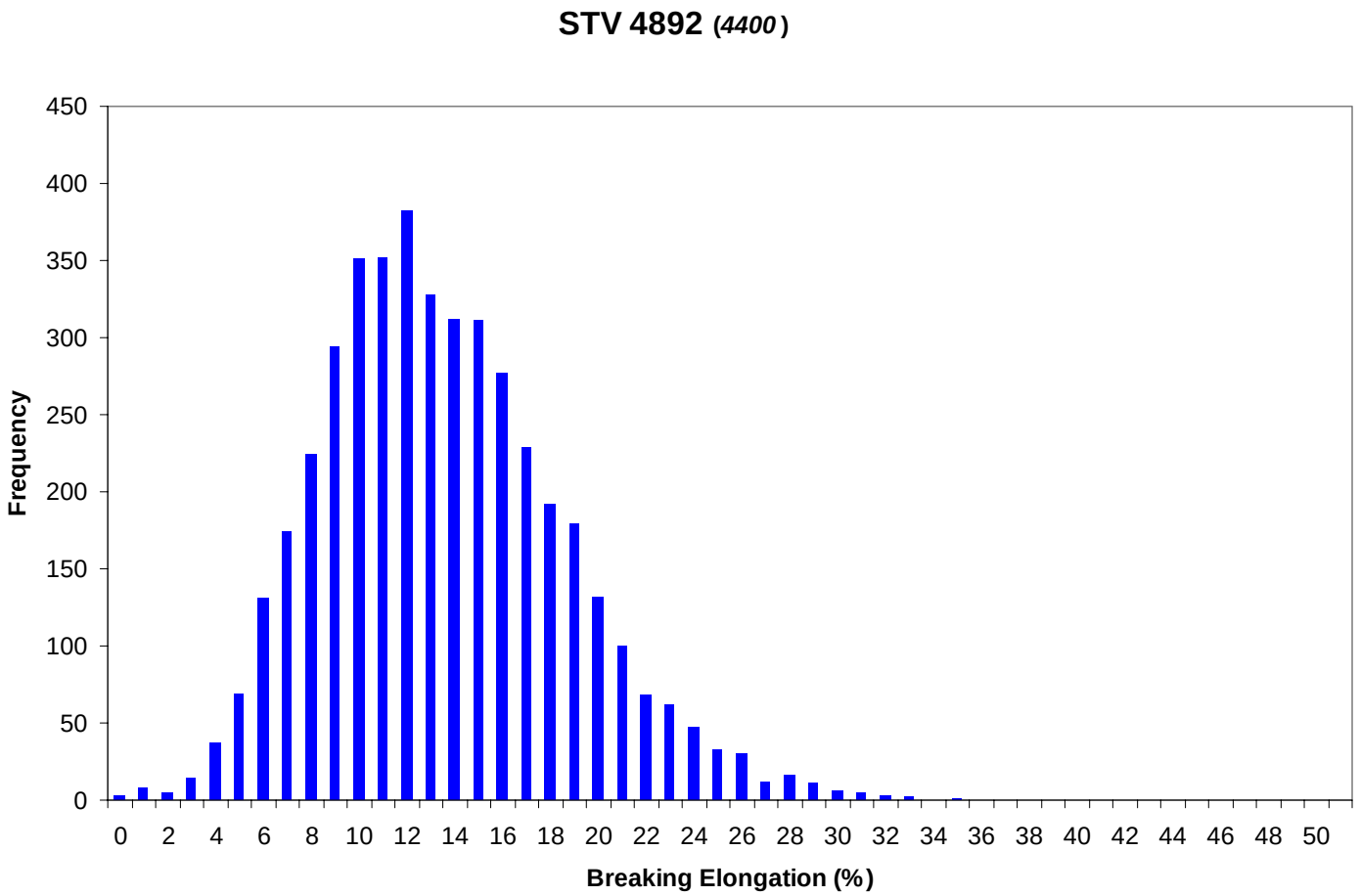

Figure 13. Histogram of Single Fiber Elongation for STV 4892 (No. of test: 4400)

5.2 Effects of Textile Processing on the Tensile Properties of Single Fibers: Sequential Property Changes from Card Slivers, Unwashed, and Washed T-shirts

We have tested cotton fibers with the Mantis® single fiber tester to obtain the tensile data at each stage of processing; raw stock, ginned cotton, card sliver, unwashed T-shirt, and washed T-shirt. The primary objective was to study how the cotton fibers are affected by the subsequent textile processing in terms of the tensile properties of cotton fibers. In order to simplify the experiment and clarify the study objectives, ginning rate, number of lint cleaners in the gin, and carding rate were selected as factors in the experimental design, as stated previously. We categorized the textile processes into two parts; dry processes from picking seed cottons up to knitting, and wet processes from finishing to laundering and drying of garments.

Figure 14 shows the average breaking strengths and breaking elongations of single fibers at each stage. Both the breaking strength and the breaking elongation decreased as the processes progressed. Since the cotton samples obtained from raw material and at ginning were not fully opened or mixed, there was obvious lack of uniformity in terms of the effects of ginning. Therefore, much uncertainty exists when we try to represent the entire stock by testing only a few thousand single fibers. The margin of errors in the ginned cotton tests is considered wide. For this reason, we focused our attention only on the tensile properties of cotton sampled in the subsequent processes; from card slivers, unwashed T-shirts, and washed T-shirts. Although it was necessary to include such processes as drawing, roving, spinning,

and knitting processes into the experimental design for more accurate investigation on the processing conditions, these processes were not examined in this study due to the limitation of time, and cost.

Figures 15 – 17 show the effects of ginning rates, number of lint cleaners, and carding rates on the breaking strength of fibers. Fibers from card slivers processed at the higher ginning rate showed a higher average breaking strength than that from the low ginning rate. However, the average fiber strengths unraveled from unwashed and washed T-shirts were shown to be higher for the fibers processed at the low ginning rate. In other words, the effects of ginning rate were reversed after carding. Since cottons were processed under exactly the same conditions except ginning and carding, we may conclude that the hidden effects of ginning and carding emerge perhaps only when the garments are washed and dried, or only when the fibers are fully relaxed. Throughout the entire processing stages, fibers processed with one lint cleaner showed higher breaking strengths than processed with two lint cleaners. Likewise, the lower carding rate produced higher average breaking strengths throughout the entire processing stages.

In addition, the decrease in the average breaking strength was shown to be progressive as the number of repeated washing/drying cycle increases. It suggests that the repeated washing/drying of garments resulted in significant damages in the tensile properties of the fibers.

Figures 18 – 20 show the effects of ginning rates, number of lint cleaners, and carding rates on the breaking elongation of fibers. Unlike the case for the breaking strength, there were no significant effects of ginning or carding rates on the breaking

elongations. However, apart from the ginning and carding effects, the decrease in breaking elongation was conspicuous as the processing continued. It was shown that the decrease in breaking elongation was quite substantial between carding and washing/drying trials. Although it was not investigated which process was the most important contributor damaging fiber tensile properties, it implied that the degradation during finishing as well as drawing, roving, spinning and knitting processes before garment production was highly significant.

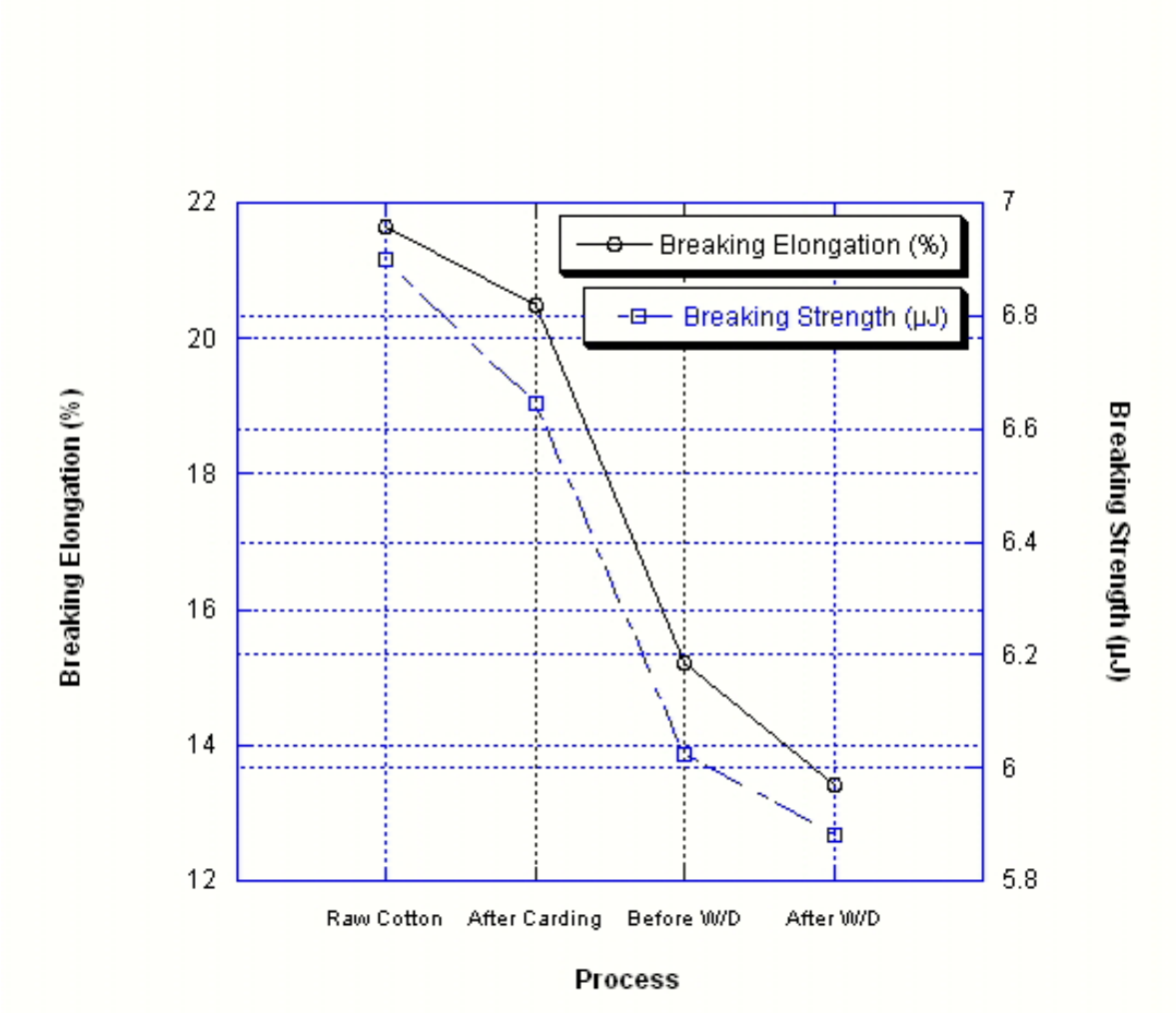

Figure 14. Average Single Fiber Breaking Strength (Elongation)* at Various Processing Stages - High Ginning, 1 Lint Cleaner, and High Carding Rate (No. of test: 21200)

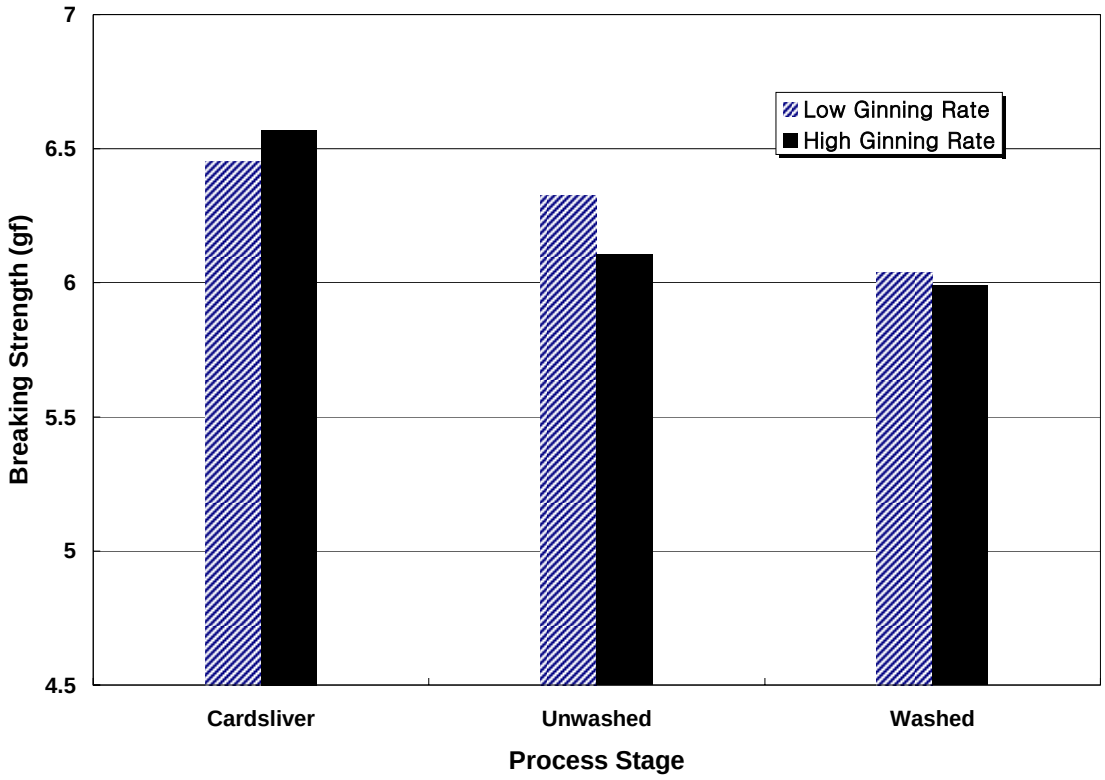

Figure 15. Average Single Fiber Breaking Strength vs. Ginning Rates (No. of test: 80727)

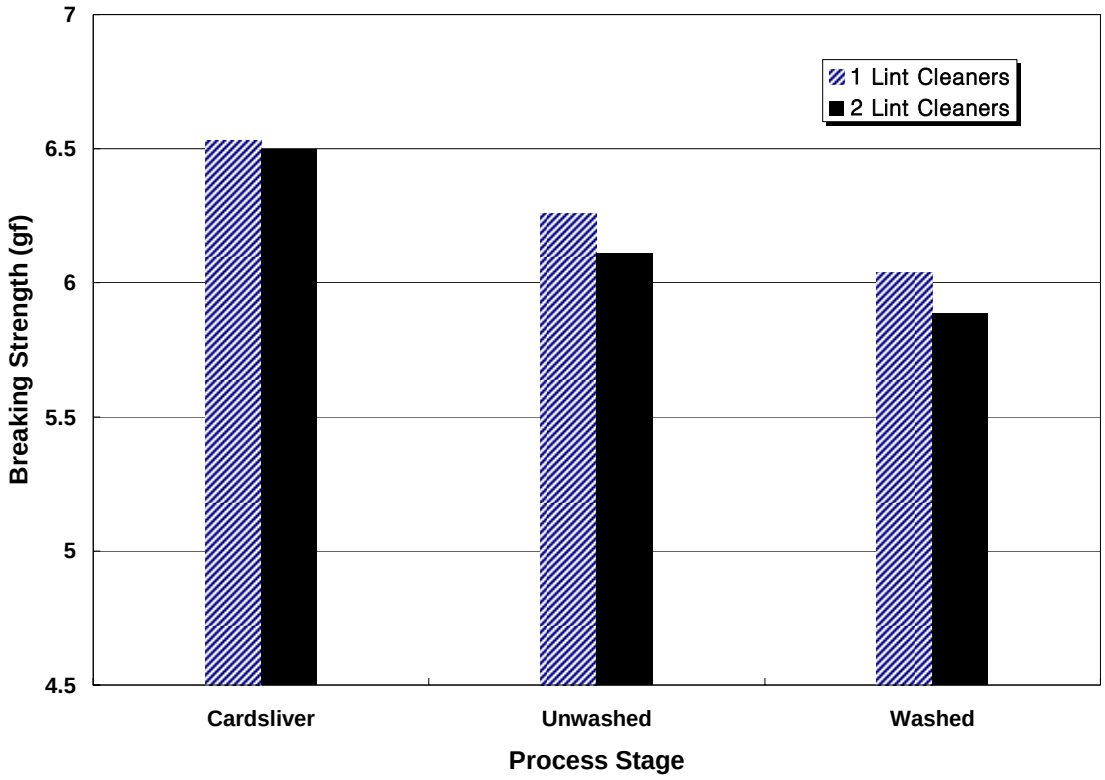

Figure 16. Average Single Fiber Breaking Strength vs. Number of Lint Cleaners (No. of test: 80727)

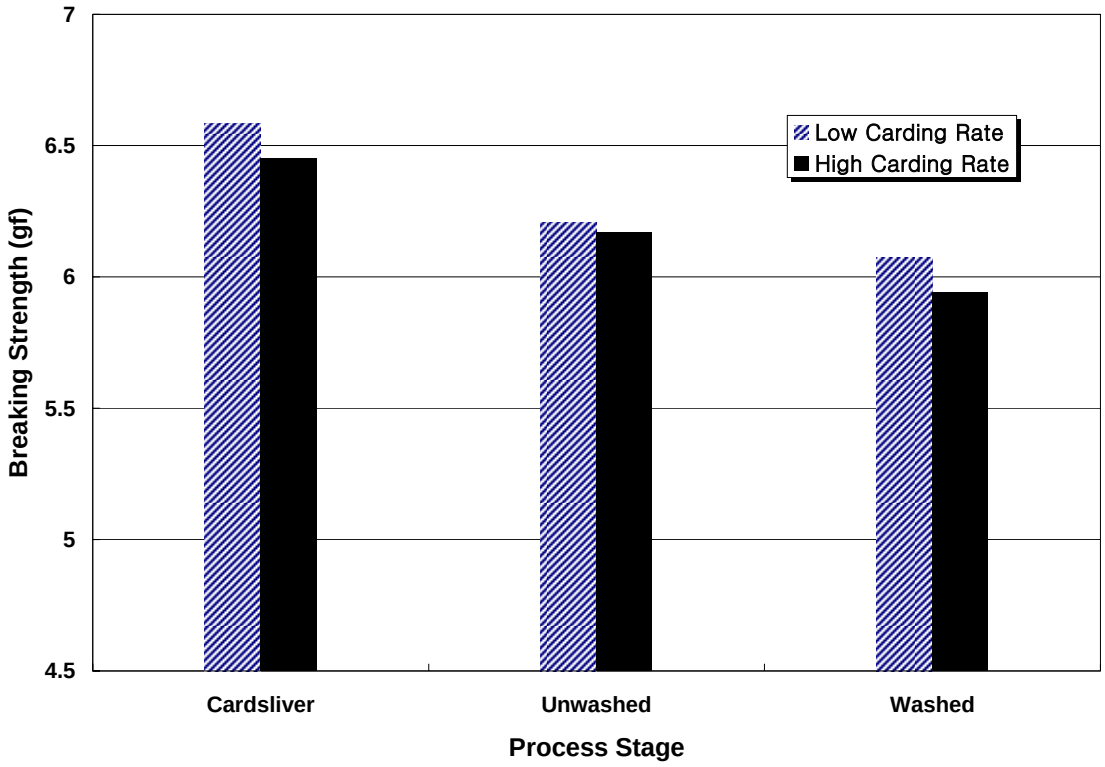

Figure 17. Average Single Fiber Breaking Strength vs. Carding Rates (No. of test: 80727)

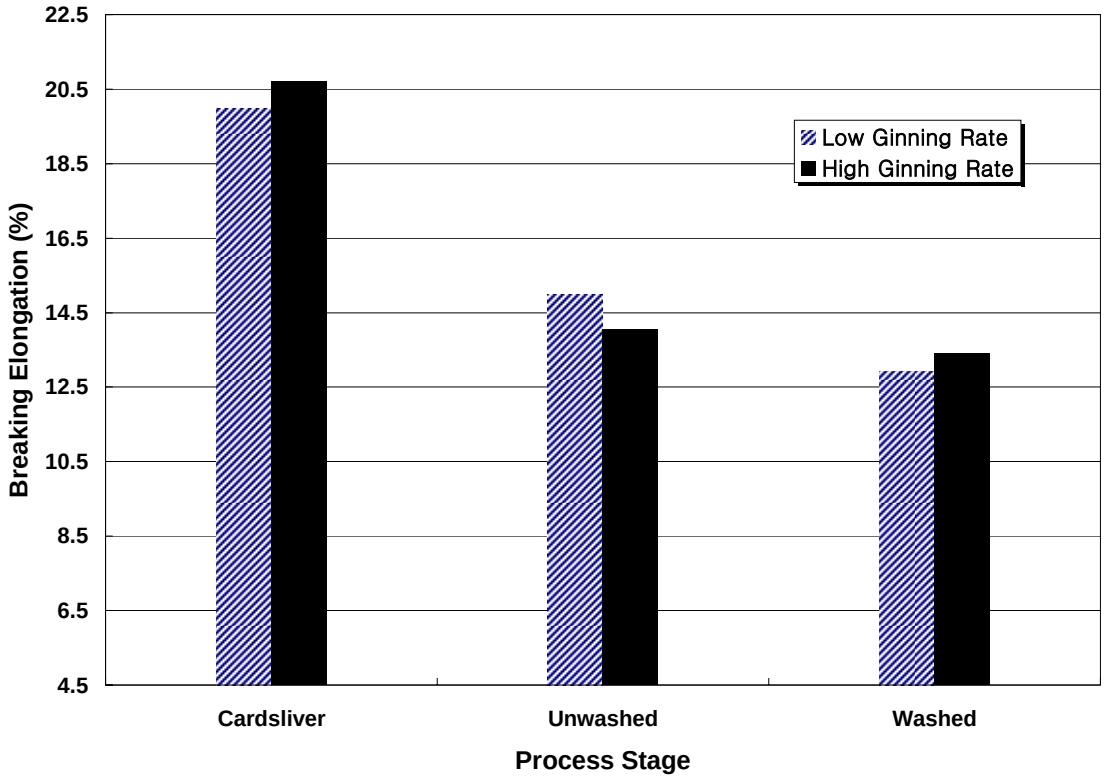

Figure 18. Average Single Fiber Breaking Elongation vs. Ginning Rates (No. of test: 80727)

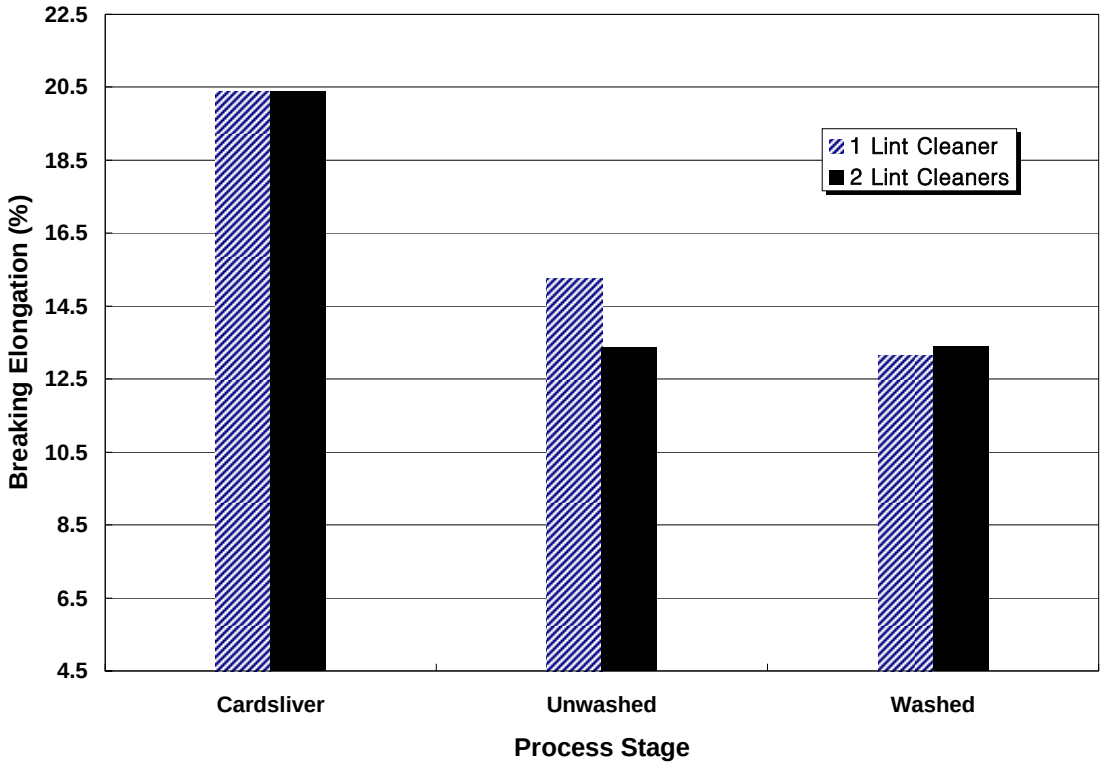

Figure 19. Average Single Fiber Breaking Elongation vs. Number of Lint Cleaners (No. of test: 80727)

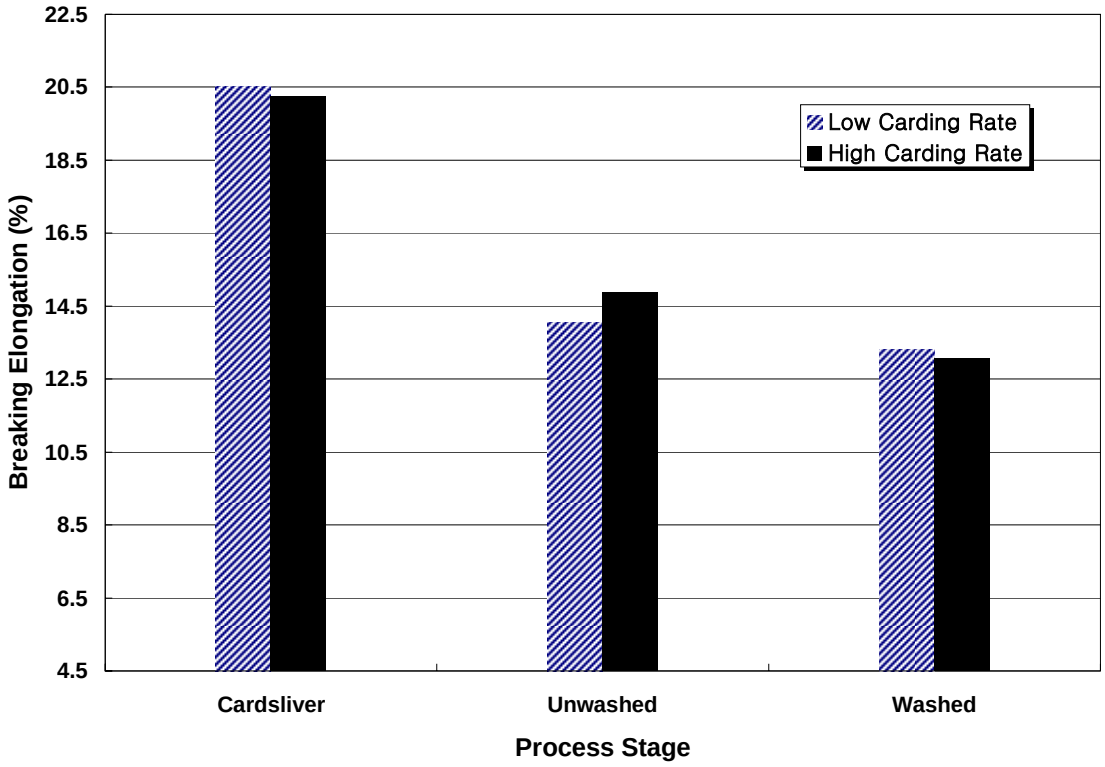

Figure 20. Average Single Fiber Breaking Elongation vs. Carding Rates (No. of test: 80727)

5.3 Study on the Tensile Properties of Cotton Fibers at Each Processing Stages

5.3.1 After Carding

STV 747, STV 4892, and DPL 33B cotton varieties were spindle-harvested, and then processed at the gin with two ginning rates and two lint cleaning methods. The ginned cotton were transferred to the card and processed under two carding rates. Then single fibers were collected after carding, and tested by Mantis® single fiber tester. For the simplification of data analysis, STV 4892 was dropped out due to their similarity to STV 747 based on the tensile property data of hand-picked and hand-ginned cotton. Statistical analysis was made on the tensile data. The results are as follows.

For this analysis, the following equation is used for regression model.

$$Y_i = \beta_0 + \beta_1 G_i + \beta_2 L_i + \beta_3 C_i + \beta_4 GL_i + \beta_5 GC_i + \beta_6 LC_i + \beta_7 GLC_i + \varepsilon \quad (8)$$

where:

Y_i = Dependent variable (Breaking strength or breaking elongation),

β_0 = Mean,

β_i, , $i=1\sim6$ = Regression coefficients,

G_i = Effect of ginning rates,

L_i = Effect of the number of lint cleaners,

C_i = Effect of carding rates,

GL_i = Interaction between ginning rates and lint cleaners,

GC_i = Interaction between ginning rates and carding rates,

LC_i = Interaction between lint cleaners and carding rates,

GLC_i = Three factor Interaction,

ε = error, and

i = 1~16 (process conditions).

Although the interaction terms were included in the above model, we could the test the null hypothesis for the interaction effect due to the insufficient degrees of freedom. Therefore, while the above model represents the full model for the analysis, we used main effect model for the following analyses.

5.3.1.1 Effects of Process Parameters on the Tensile Properties of STV 747 Cotton Fibers

All three process variables (ginning rate, number of lint cleaners, and carding rate) had significant effects on the breaking strength. Average breaking strength of fibers from the higher ginning rate was greater than that at lower ginning rate by 0.25 gf. Fibers ginned with one lint cleaner showed a higher breaking strength than with two lint cleaners by 0.11 gf. Fibers carded at lower rate showed higher breaking strength than that at higher rate by 0.13 gf.

Fibers undergone higher ginning rate also showed a greater breaking elongation than that of lower ginning rate by 1.19%. All this difference was significant at 5% error level. The number of lint cleaners and carding rates, however, did not have significant effects on breaking elongation.

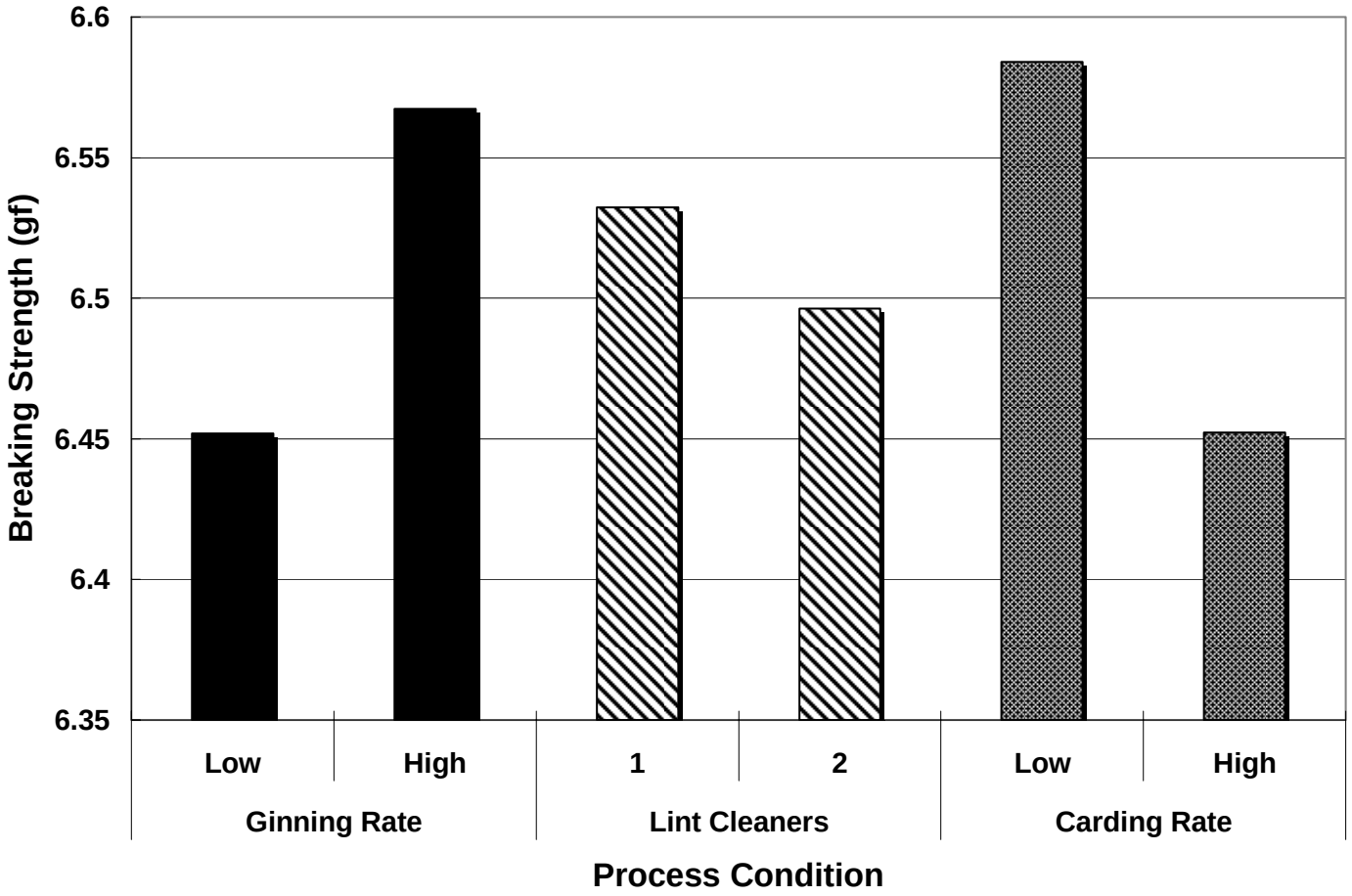

Figure 21. Fiber Strength of STV 747 Card Slivers vs. Ginning Rates, No. of Lint Cleaner, and Carding Rates (No. of test: 22798)

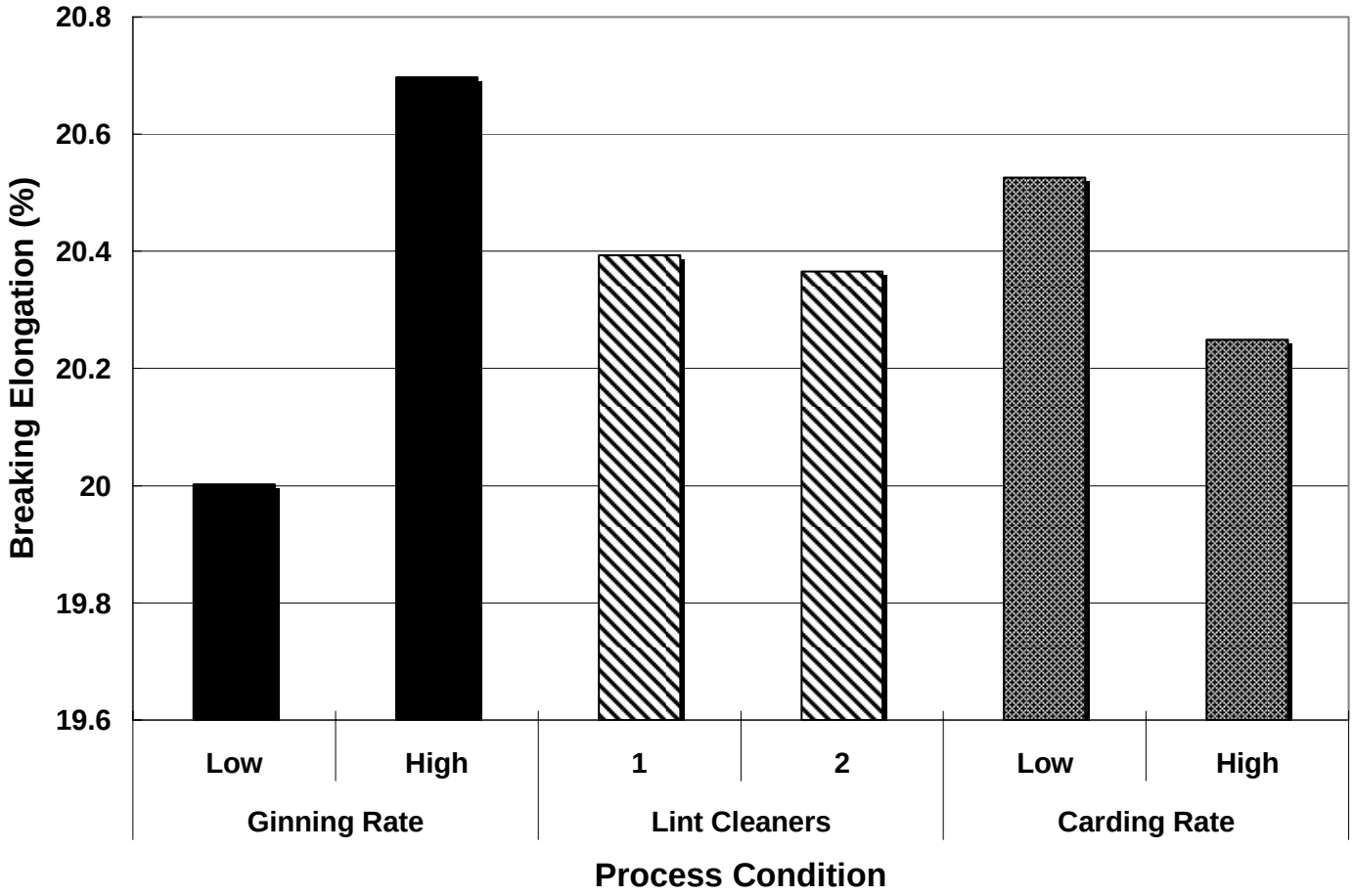

Figure 22. Fiber Elongation of STV 747 Card Slivers vs. Ginning Rates, No. of Lint Cleaner, and Carding Rates (No. of test: 22798)

5.3.1.2 Effects of Process Parameters on the Tensile Properties of DPL 33B Cotton Fibers

The ginning rates did not have a significant effect on the breaking strength. Fibers ginned with one lint cleaner showed greater breaking strengths than that with two lint cleaners by 0.29 gf, and the difference was significant at 5% error level. The carding rates also showed a significant effect on the breaking strength. Fibers carded at the lower rate showed a higher breaking strength than that at higher rate by 0.1 gf. The result was significant at 5% error level.

The effect of ginning rate was not significant for the breaking elongation. On the other hand, other two process parameters showed significant effects on the breaking elongation. Fibers ginned with one lint cleaner showed greater breaking elongations than that with two lint cleaners by 0.8%. Fibers carded at lower rate also showed higher breaking elongations than that at higher rate by 0.27%. Both figures were significant at 5% error level.

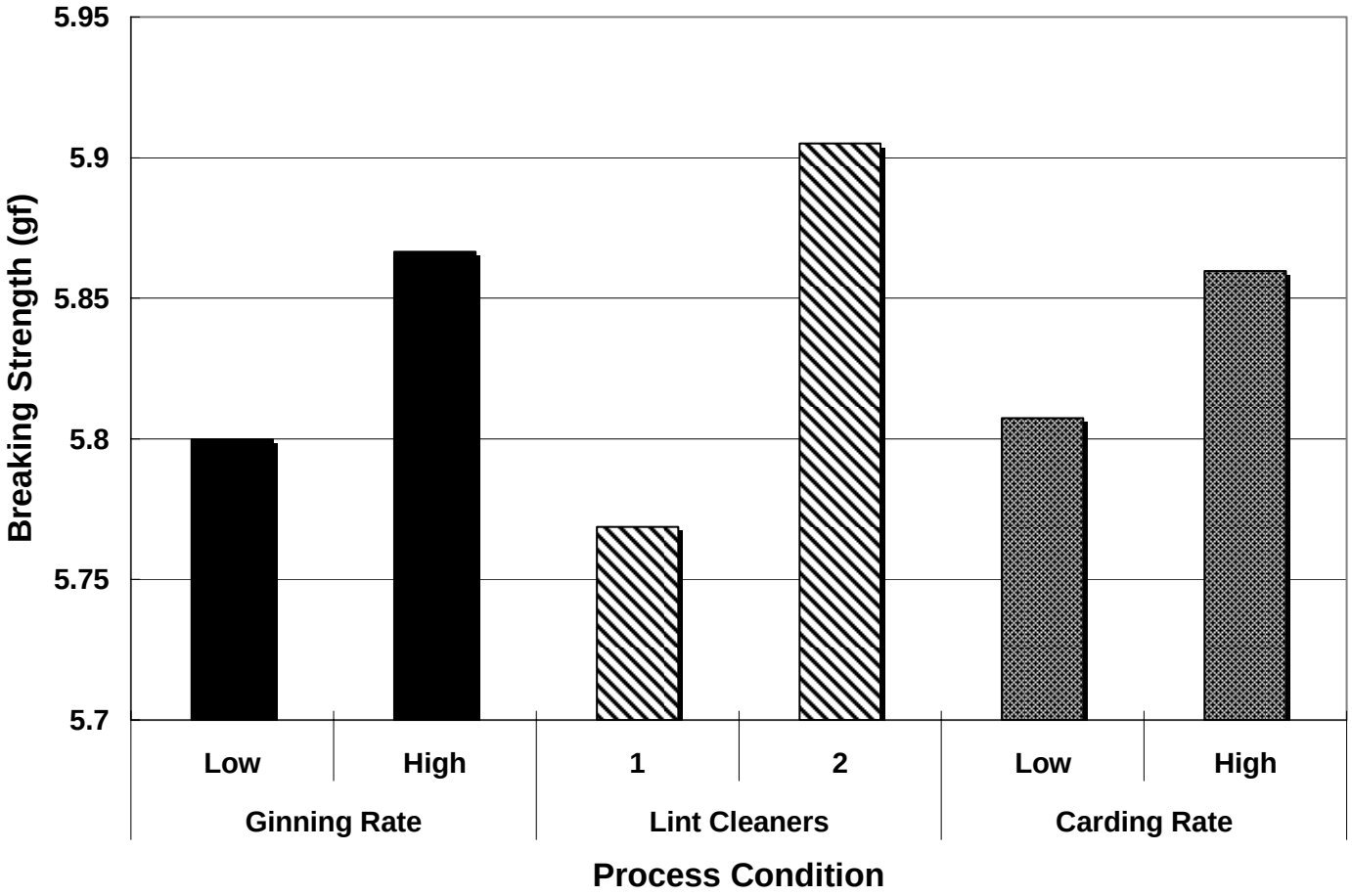

Figure 23. Fiber Strength of DPL 33B Card Slivers vs. Ginning Rates, No. of Lint Cleaner, and Carding Rates (No. of test: 22396)

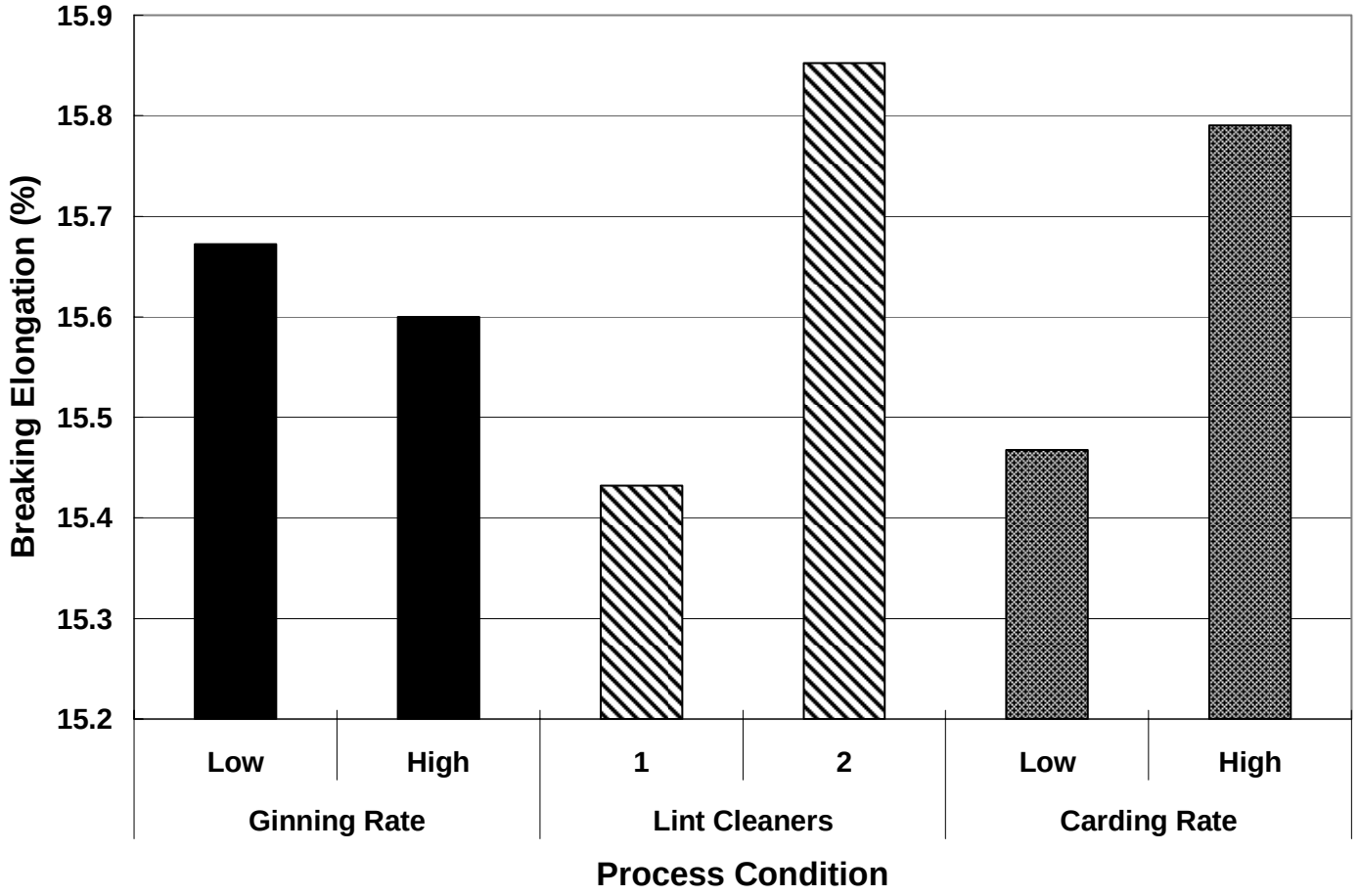

Figure 24. Fiber Elongation of DPL 33B Card Slivers vs. Ginning Rates, No. of Lint Cleaner, and Carding Rates (No. of test: 22396)

5.3.1.3 Summary

Fibers collected after carding were individually tested and tensile property data were obtained by Mantis® single fiber tester. Statistical analyses showed that the ginning rates, number of lint cleaners, and the carding rates seemed to be significant for affecting tensile properties of STV cotton fibers, and DPL cotton fibers showed similar trend on the processing variables except ginning rate. The difference between two varieties of cotton is possibly originated from the intrinsic genetic properties of the fiber which are obtained by the differences in genes and growing environment. The increase in ginning rate in the range of the experimental design turned out to be favorable on the breaking strength, while decreased the breaking elongation. This phenomenon will be discussed in the sections of theoretical consideration. From the results about the effects of the carding rates and the number of lint cleaners, it could be considered that during opening and cleaning processes after ginning, the more and harsh actions would damage the cotton fiber more in terms of the tensile properties.

5.3.2 Before Repeated Washing and Drying of Garments

Cotton T-shirts were manufactured from the fibers undergone 8 different processing. Due to limited time and labor for the experimental design, only the STV 747 cotton was used for manufacturing T-shirts and the subsequent tests.

For the objective of this section, we tried to test as many fibers from T-shirts as possible in order to facilitate proper statistical evaluation of the effects of ginning and carding methods. Therefore, a total of 6000 - 8000 fibers were tested for each of the four T-shirts in order to obtain the statistical significance of the effects being studied in Tables 10 - 11.

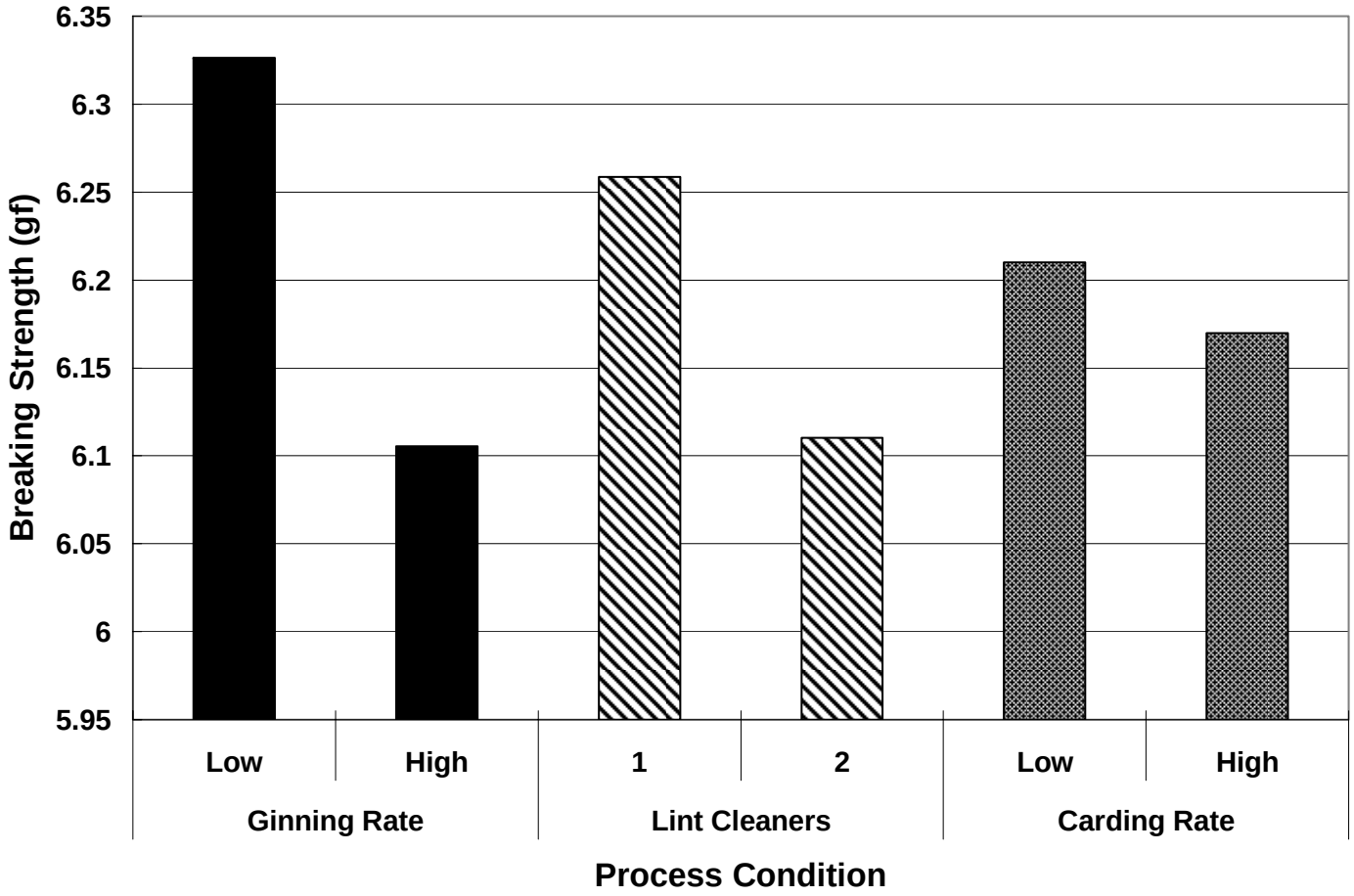

Figure 25. Fiber Strength of STV 747 Unwashed T-shirts vs. Ginning Rates, No. of Lint Cleaner, and Carding Rates (No. of test: 34399)

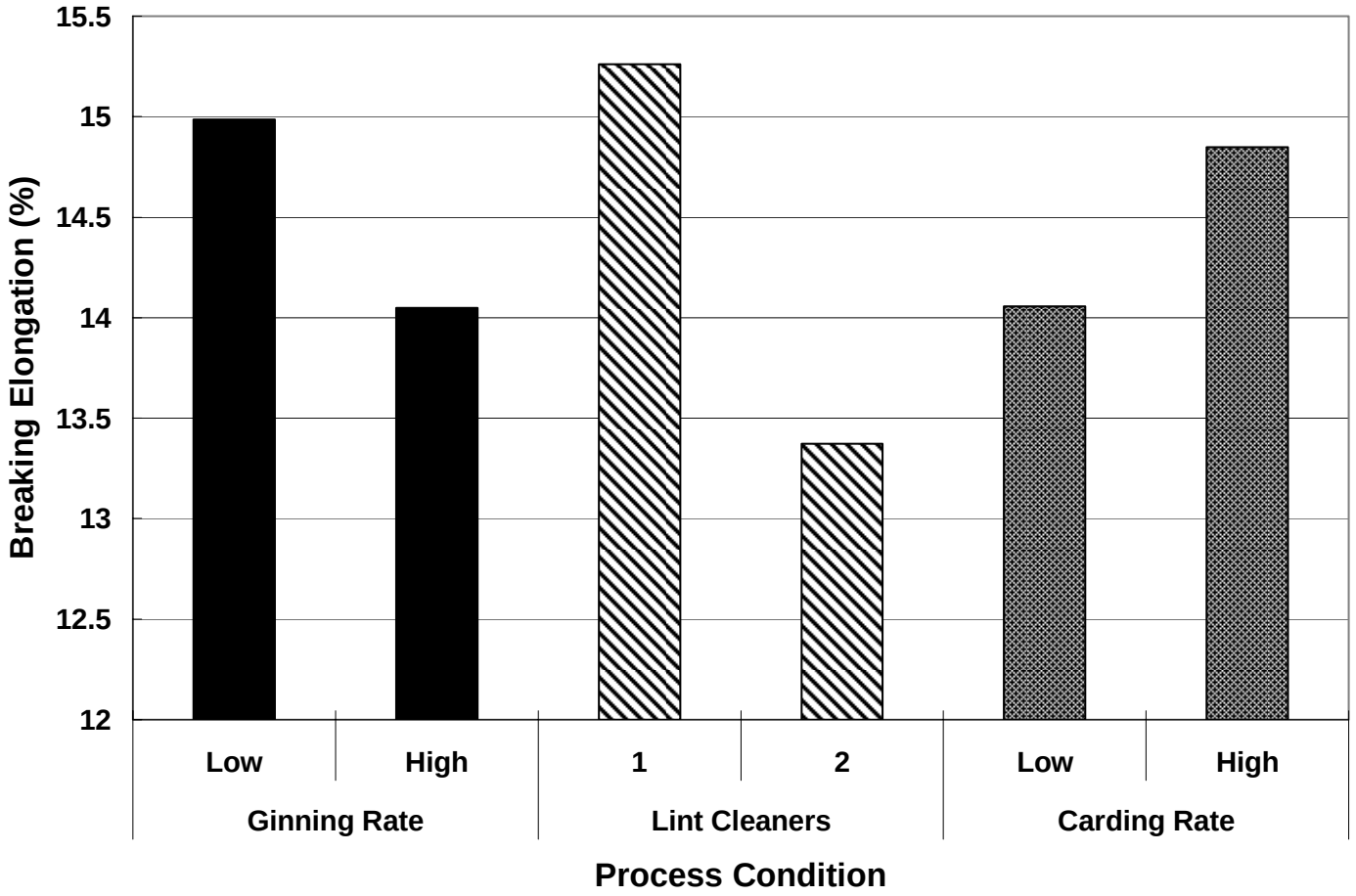

Figure 26. Fiber Elongation of STV 747 Unwashed T-shirts vs. Ginning Rates, No. of Lint Cleaner, and Carding Rates (No. of test: 34399)

Table 10. ANOVA for Processing Effects on Breaking Strength of Single Fibers from Various Unwashed T-shirts

GLM Procedure

Class Level Information

Class	Levels	Values
Gin	2	1 2
Lint	2	1 2
Card	2	1 2

Number of observation 34400

Dependent Variable: Breaking Strength (gf)

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	283.7086	94.5695	22.43	<.0001
Error	34396	145003.6021	4.2157		
Corrected Total	34399	145287.3106			

Root MSE	2.053220	R-square	0.0019
Dependent Mean	6.011048	Coeff. Var.	34.157

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Gin	1	22.3876401	22.3876401	5.31	0.0212
Lint	1	107.5691590	107.5691590	25.52	<.0001
Card	1	153.7517829	153.7517829	36.47	<.0001

Table 11. ANOVA for Processing Effects on Breaking Elongation of Single Fibers from Various Unwashed T-shirts

GLM Procedure

Class Level Information

Class	Levels	Values
Gin	2	1 2
Lint	2	1 2
Card	2	1 2

Number of observation 34400

Dependent Variable: Breaking Elongation (%)

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	2334.4527	778.1509	29.33	<.0001
Error	34396	912551.5629	26.5307		
Corrected Total	34399	914886.0156			

Root MSE	5.150801	R-square	0.0025
Dependent Mean	13.20610	Coeff Var	39.003

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Gin	1	1919.536599	1919.536599	72.35	<.0001
Lint	1	3.374959	3.374959	0.13	0.7213
Card	1	411.541096	411.541096	15.51	<.0001

Tables 12 –15 show the summary statistics of tensile properties of single fibers from unwashed T-shirts.

Table 12. Summary Statistics for Tensile Properties of Single Fibers Undergone Various Ginning and Carding Conditions - Unraveled from Unwashed T-shirts

Ginnig Rate	No. of Lint Cleaners	Carding Rates	Tensile Properties	No. of Tests	Mean	Std. Dev.	Notation
Low	1	Low	BS	7200	6.23	2.17	S-111
			BE		15.42	6.01	
			BW		15.30	7.99	
		High	BS	6000	6.40	2.16	S-112
			BE		14.86	5.73	
			BW		15.34	8.06	
High	1	Low	BS	6000	6.48	2.25	S-211
			BE		15.53	5.76	
			BW		16.11	8.39	
		High	BS	8400	6.02	2.02	S-212
			BE		15.22	5.88	
			BW		15.01	7.90	
	2	Low	BS	8000	5.87	2.33	S-221
			BE		15.28	4.78	
			BW		15.19	7.33	
		High	BS	8000	6.15	2.09	S-222
			BE		14.47	5.46	
			BW		14.62	7.64	

The ANOVA (Table 10) for the breaking strength shows that all factors except the ginning rates influenced the breaking strength of single fibers based on the tests on fibers from unwashed T-shirt fibers. From Table 14, we could see that the fibers ginned with 1 lint cleaner had higher breaking strengths than that with 2 lint cleaners, and that the fibers carded at low rate had higher breaking strengths than that from the higher carding rate in Table 15. This signifies the differences in fiber damages due to the high carding rate and the additional lint cleaning action.

For the breaking elongation, we could see that ginning and carding rates affected the breaking elongation of fibers unraveled from the unwashed T-shirts as shown in Table 11. The higher ginning rate, 2 lint cleaner and higher carding

rate produced the lowest average breaking elongation based on the fibers taken from unwashed T-shirts.

Table 13. Summary Statistics for Tensile Properties of Fibers Unraveled from Unwashed T-shirts in Terms of Ginning Rate

Ginning Rate	No. of Tests	Breaking Strength (gf)				Breaking Elongation (%)			
		Mean	Std Dev.	Min.	Max.	Mean	Std Dev.	Min.	Max.
Low	14400	6.041	2.052095	0.41	17.58	12.93	5.062395	0.61	54.87
High	20000	5.989	2.057105	0.43	17.59	13.41	5.215259	0.83	50.57

Table 14. Summary Statistics for Tensile Properties of Fibers Unraveled from Unwashed T-shirts in Terms of No. of Lint Cleaners

No. of Lint Cleaners	No. of Tests	Breaking Strength (gf)				Breaking Elongation (%)			
		Mean	Std Dev.	Min.	Max.	Mean	Std Dev.	Min.	Max.
1	27600	6.042	2.055588	0.41	17.59	13.16	5.163169	0.77	54.87
2	6793	5.887	2.048802	0.43	16.1	13.39	5.129035	0.83	37.78

Table 15. Summary Statistics for Tensile Properties of Fibers Unraveled from Unwashed T-shirts in Terms of Carding Rate

Carding Rate	No. of Tests	Breaking Strength (gf)				Breaking Elongation (%)			
		Mean	Std Dev.	Min.	Max.	Mean	Std Dev.	Min.	Max.
Low	18400	6.074	2.067654	0.41	17.59	13.32	5.205302	0.83	54.87
High	16000	5.939	2.038343	0.46	17.58	13.07	5.098184	0.61	46.48

5.3.3 After Repeated Washing and Drying of Garments

After 32 repeated washing/drying cycles, several T-shirts were selected for the tensile testing of single fibers based on the ginning and carding conditions. From each group of T-shirts undergone the same process condition, roughly 3000 - 7000 fibers were collected and tested on Mantis®. The summary statistics for the tensile properties of fibers taken at each process condition are shown in Table 16. Due to the time and labor limitations, we had tested fibers from selective groups of T-shirts. The statistical analyses were using SAS® and the ANOVA tables are shown in Tables 17 and 18. The summary statistics for the ginning, lint cleaning and carding conditions are shown in Tables 19, 20, and 21.

Table 16. Summary Statistics for Tensile Properties of Single Fibers Undergone Various Ginning and Carding Conditions - Unraveled from Washed T-shirts

Ginnig Rate	No. of Lint Cleaners	Carding Rates	Tensile Properties	No. of Tests	Mean	Std. Dev.	Notation
Low	1	Low	BS	7200	6.068	2.060	S-111
			BE		13.029	5.165	
			BW		12.846	6.814	
		High	BS	7200	6.015	2.044	S-112
			BE		12.827	4.956	
			BW		12.735	6.728	
High	1	Low	BS	7600	6.162	2.069	S-211
			BE		13.408	5.229	
			BW		13.531	7.248	
		High	BS	5600	5.879	2.036	S-212
			BE		13.427	5.301	
			BW		13.074	7.244	
	2	Low	BS	3600	5.899	2.070	S-221
			BE		13.724	5.205	
			BW		13.209	7.001	
		High	BS	3200	5.874	2.025	S-222
			BE		13.011	5.017	
			BW		12.655	6.869	

The ANOVA for the breaking strength shows that every factor except ginning rates influenced the breaking strength of single fibers based on the washed T-shirts. From Tables 20 and 21, we could see that the fibers ginned with 1 lint cleaner had higher breaking strengths than that from 2 lint cleaners. Also, the fibers carded at the low rate showed a higher average breaking strength than that from the higher carding rate.

For the breaking elongation, it is found that all ginning and carding conditions affected the breaking elongation of single fibers unraveled from washed T-shirts.

Based on the results of tensile tests of cotton fibers from washed T-shirts, it was clear that the effects of ginning and carding conditions existed even after

the repeated washing/drying of garments. Higher processing rates and additional lint cleaning processes lowered both the average breaking strength and elongation.

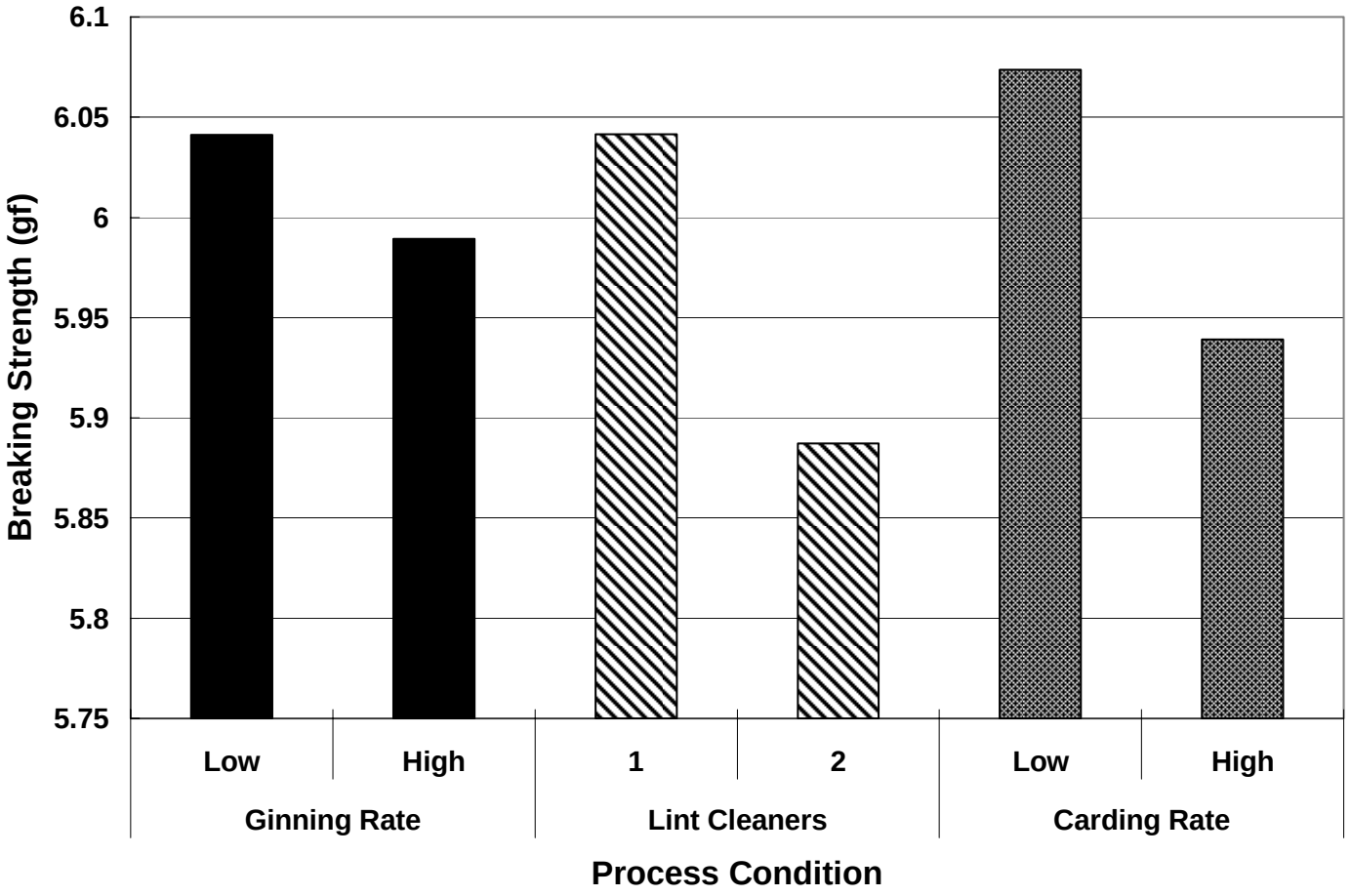

Figure 27. Fiber Strength of STV 747 Washed T-shirts vs. Ginning Rates, No. of Lint Cleaner, and Carding Rates (No. of test: 23530)

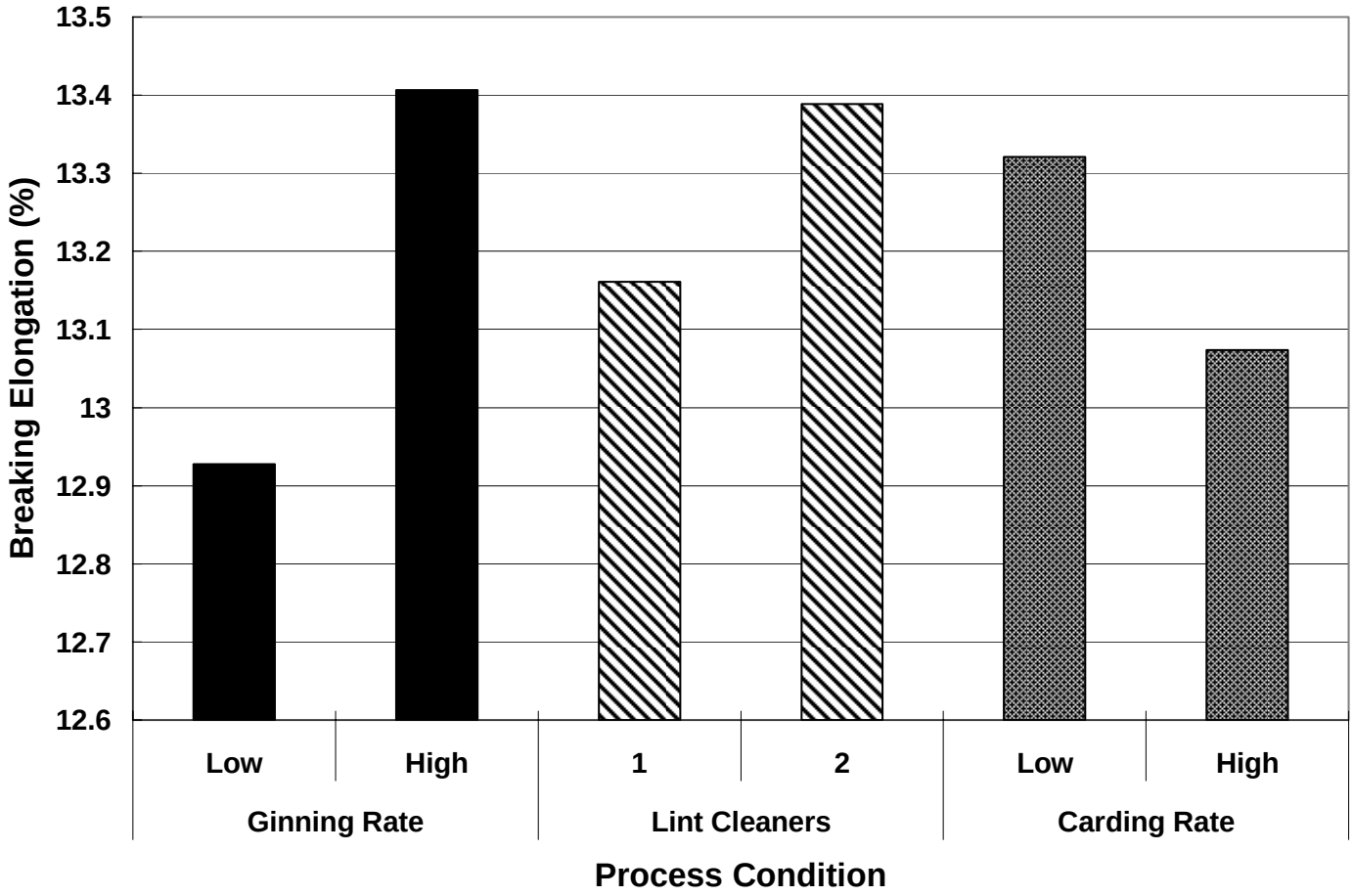

Figure 28. Fiber Elongation of STV 747 Washed T-shirts vs. Ginning Rates, No. of Lint Cleaner, and Carding Rates (No. of test: 23530)

Table 17. ANOVA for Processing Effects on Breaking Strength of Single Fibers from Various T-shirts Undergone 32 Repeated W/D

GLM Procedure

Class Level Information

Class	Levels	Values
Gin	2	1 2
Lint	2	1 2
Card	2	1 2

Number of observation 23531

Dependent Variable: Breaking Elongation (%)

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	255.25904	85.08635	20.26	<.0001
Error	23527	98817.26577	4.20016		
Corrected Total	23530	99072.52482			

Root MSE	2.049430	R-square	0.002576
Dependent Mean	5.982753	Coeff Var	34.25564

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Gin	1	15.8962681	15.8962681	3.78	0.0517
Lint	1	73.3842369	73.3842369	17.47	<.0001
Card	1	165.9785397	165.9785397	39.52	<.0001

Table 18. ANOVA for Processing Effects on Breaking Elongation of Single Fibers from Various T-shirts Undergone 32 Repeated W/D

GLM Procedure

Class Level Information

Class	Levels	Values
Gin	2	1 2
Lint	2	1 2
Card	2	1 2

Number of observation 23531

Dependent Variable: Breaking Elongation (%)

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	2828.1901	942.7300	36.15	<.0001
Error	23527	613545.7173	26.0784		
Corrected Total	23530	616373.9074			

Root MSE	5.106698	R-square	0.004588
Dependent Mean	13.34985	Coeff Var	38.25285

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Gin	1	2095.046820	2095.046820	80.34	<.0001
Lint	1	216.531014	216.531014	8.30	0.0040
Card	1	516.612248	516.612248	19.81	<.0001

Table 19. Summary Statistics for Tensile Properties of Fibers Unraveled from Washed T-shirts in Terms of Ginning Rate

Ginning Rate	No. of Tests	Breaking Strength (gf)				Breaking Elongation (%)			
		Mean	Std Dev.	Min.	Max.	Mean	Std Dev.	Min.	Max.
Low	6792	6.024	2.045352	0.5	17.58	12.88	4.95248	0.16	46.46
High	16739	5.966	2.054444	0.43	16.1	13.54	5.171891	0.16	50.57

Table 20. Summary Statistics for Tensile Properties of Fibers Unraveled from Washed T-shirts in Terms of No. of Lint Cleaners

No. of Lint Cleaners	No. of Tests	Breaking Strength (gf)				Breaking Elongation (%)			
		Mean	Std Dev.	Min.	Max.	Mean	Std Dev.	Min.	Max.
1	16738	6.022	2.052593	0.49	17.58	13.33	5.120024	0.16	50.57
2	6793	5.886	2.04729	0.43	16.1	13.4	5.113453	0.16	37.78

Table 21. Summary Statistics for Tensile Properties of Fibers Unraveled from Washed T-shirts in Terms of Carding Rate

Carding Rate	No. of Tests	Breaking Strength (gf)				Breaking Elongation (%)			
		Mean	Std Dev.	Min.	Max.	Mean	Std Dev.	Min.	Max.
Low	9944	6.054	2.067655	0.43	15.55	13.69	5.189321	0.16	50.57
High	13587	5.931	2.03887	0.46	17.58	13.1	5.050697	0.16	46.48

5.4 Possible Model for Strength of Cotton Fibers

5.4.1 Structural Characteristics and Mechanical Properties of Cotton Fiber

In order to assess the effects of processing conditions on cotton fibers, it is necessary to examine how the mechanical properties of a fiber are decided by the structural properties.

While the conventional norm may call for a lower breaking strength at a higher process rate, the changes in the degree of orientation and the micro-mechanical structure of cotton fiber, must be examined to explain some of the unexpected experimental results. The discussion here is to formulate a possible model for explaining tensile behaviors of cotton fibers based on the fiber structures.

5.4.2 Fibrillar Layers in a Cotton Fiber and Their Tensile Behaviors

Cotton fiber is known to have a highly ordered structure. The previous researchers [70-75] found that cotton is an assembly of fibrils which are aligned at certain angles to the fiber axis. The early studies were based on the assumption that these fibrils were aligned at a constant angle throughout the assembly, and this assumption led to a uniform strain rate under stress throughout the fiber thickness. However, other studies found that the angle of the inner fibrillar layer is more aligned to the fiber axis than the outer layer [76-81]. Some researchers found that this difference in the degree of orientation resulted in different responses to the extensional force to the fiber. Based on this

information, the study begins with the assumption that the inner and outer fibrils show different fibrillar angles.

A cotton fiber is known to have many fibrillar layers. When a fiber is subjected to axial loading, each layer is thought to be elongated exhibiting different levels of stress. Since the fibrillar angles are greater for outer layers, the axial loading changes the angle continuously as the elongation increases, thus creating different amounts of changes in the fibrillar angle from core to surface. That is, if the fibrils form more angle with the axis of the fiber, the amount of extension would be greater. Since outer fibrils form more angle with the fiber axis, they are subjected to less stress under initial loading of the fiber as they are straightened out without fibrillar elongation. On the other hand, inner fibrils have limited amount of slack under axial loading of the fiber, thus subjecting them to a higher initial stress. When the fiber is stretched, the inner fibrillar layers reach the breaking extension before the outer layers. As the extension continues, the fibrils in inner layers are broken first while the outer fibrils are continuously stretched. When the fibrils in a inner layer break, the load would drop abruptly before rising again along with extension of the outer fibrils. Based on this assumption, it should be understood that the cumulative load at any given extension of a fiber is due to the two load components realized by the inner and outer fibrillar layers.

How these different responses give rise to the ultimate breaking strength and breaking elongation is shown in the appendix A.

5.4.3 Results and Discussion: Interpretation of the Results in Terms of Inner-outer Fibrils Theory

The data from experimental design suggest that the breaking strength as well as breaking elongation definitely decrease due to ginning and carding in general. These are based on the raw cotton tensile data and the average tensile performance data obtained from card slivers. The factorial design provided the main effects showing the effects of ginning rate, number of lint cleaners and carding rate.

On the effects of ginning rate, however, the results may lead to one question how the higher carding rate could generate a higher breaking strength. This unexpected phenomenon can be explained easily by examining the structure as to how the breaking strength is realized from the two-layer system described previously for the inner and outer fibrils. In Figure 29 (a), (b) and (c), the realignment of the inner and outer layers due to high and low ginning rates is explained. Assuming that the two layers have differing amounts of “slack” as a bundle, the original structure (a) is shown to undergo two different realignments for generating two different load-extension diagrams; (b) for cotton fibers ginned at a lower rate and (c) at a higher rate. Without loss of generality, we assume that slack for the inner layer was zero to begin with. The original slack for the outer layer shown in (a) then will be reduced by an amount equal to e_1 for (b) and e_2 for (c) when e_1 and e_2 are assumed to be the unrecovered amounts of extension at the end of low rate ginning and high rate ginning, respectively. Then, the inner layer will be broken at an extension lower than the original

breaking extension in (a) by e_1 for the fibers ginned at the lower rate and similarly by e_2 for the fibers ginned at the higher rate. For simplicity, we assume that breaking loads remain at $\mathcal{L}_0$ for all three cases.

For the outer layer, however, the shape of the load-extension diagrams in (b) and (c) is changed by assuming the e_1 and e_2 are both smaller than the original slack for the outer layer in (a). The net changes, then come from the shifting of the load-extension curve for the outer layer closer to the zero extension point by e_1 and e_2, respectively, for the fibers ginned at the lower and higher rates. For defining the ultimate strength of the ginned fibers, the amounts of load contributed by the outer layers become the critical factor. As it is clear from the foregoing logic and Figure 29 (a), (b) and (c), $s_2 > s_1 > s_0$ can be easily established based on the above assumptions.

Hypothetically, the strength could be realized when the outer layer breaks instead of the breakage point of the inner layer in the above example. This may be unlikely in ginning, the first processing stage. If such is the case, the strength loss would be substantial as perhaps would be the case in carding and the subsequent textile processes, namely, roving, spinning, winding, knitting and finishing.

In reality, the ultimate strengths and the load-extension curves for the inner and outer layers of ginned cotton may be shallower than that of the raw cotton before ginning. For illustration of the proposed theory, however, the

tensile degradation expressible by the load-extension diagrams is not accounted for.

In terms of the classical bundle strength theory, the above illustration can be called “length equalization process” when the constituent filaments in a bundle have different amounts of slack for whatever reasons. The so-called “conditioning” in the strength tests of synthetic filaments is directly relevant to the strength tests of single fibers discussed here.

Here, the explanation is much easier when the inner and outer fibrils are assumed to have different amount of slack as evidenced by the work of other researchers.

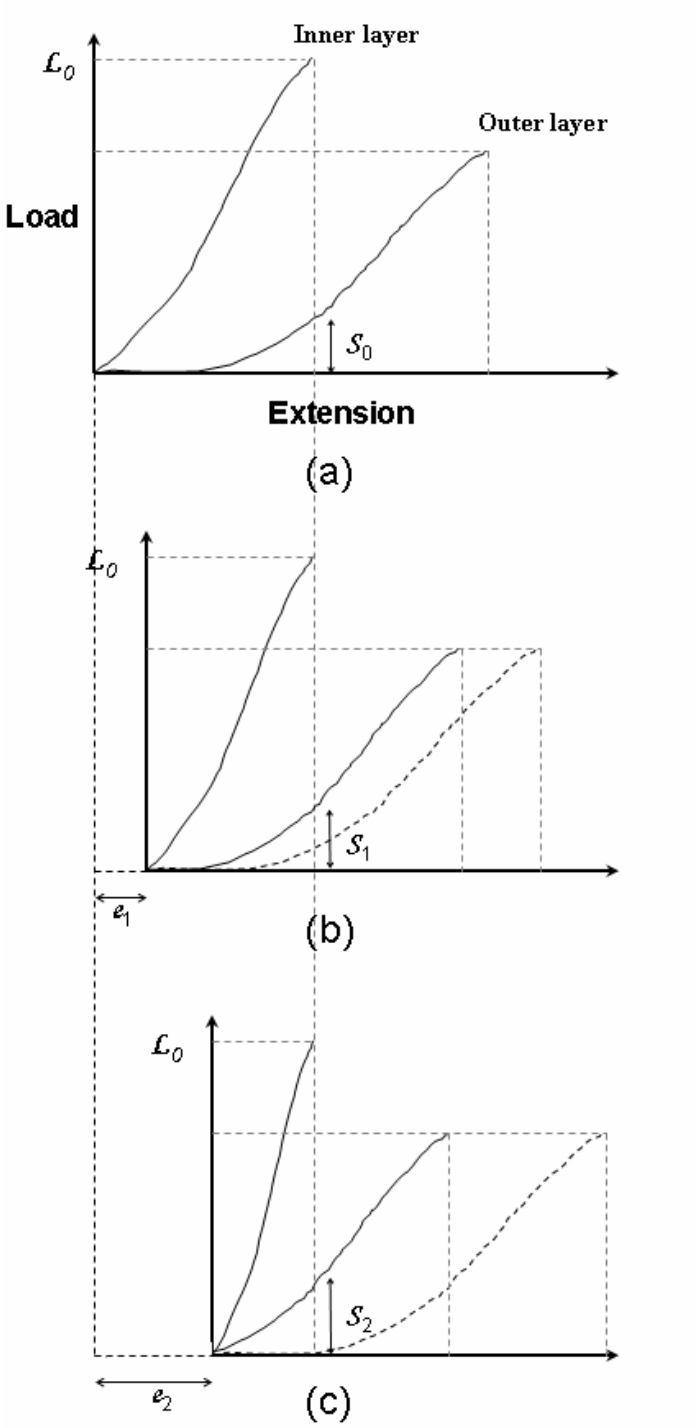

Figure 29. Theoretical Tensile Response of Cotton Fibers; (a) Before Ginning; (b) After Low Ginning; (c) After High Ginning

5.5 Relationships Between Single Fiber Tensile Properties and the Amount of Shrinkage of T-shirts after Repeated Washing/Drying

Measurements were made on the length and width shrinkages of T-shirts produced from fibers that had been processed under various ginning and carding conditions. The progressive shrinkages of STV 747 and DPL 33B T-shirts are plotted in Figures 30- 33. The progressive length shrinkages of both T-shirts are shown in Figure 30 and Figure 31. At the end of 4 washing and drying cycles, the length shrinkage increased significantly, but from then on the additional progressive shrinkages up to 32 cycles were not significant. The progressive width shrinkages of both T-shirts are shown in Figure 32 and Figure 33. For the width, the shrinkage features were quite different from that of length; the shrinkage increased up to 4 cycles, but the T-shirts actually expanded between 8 and 12 cycles, and then shrank back again. Based on these, it was difficult to see the overall shrinkage behaviors without combining the length and width shrinkages together. Statistical analyses were performed on the length and width shrinkage of 16 T-shirts (2 replicates for the 8 different processing conditions) after 32 cycles of washing and drying. We found that only the number of lint cleaners produced significant differences in the length and width shrinkages at 5 % error level. The ANOVA tables for the length and width shrinkages are shown in Appendix. T-shirts in which fibers were ginned with 2 lint cleaners had less length shrinkage than that with 1 lint cleaner. For the width shrinkage, ANOVA showed that the number of lint cleaners affected the shrinkage after 32 washing/drying cycles; The T-shirts with which the fibers were ginned with

2 lint cleaners showed more shrinkage than that with 1 lint cleaner. Based on the above results, it seemed that there was negative correlation between the length and the width shrinkages. However, there were no definite effects of ginning and carding conditions except the number of lint cleaners on these one dimensional shrinkages. In addition, as was shown in the progressive shrinkage in the width direction, some T-shirts actually expanded at the end of the washing and drying cycles. Although the length shrinkage is generally considered to be our prime concern, its relationship with the dimensional changes in width is also important. For this reason, analyses were made on the area shrinkage as well. The analyses were to study the effects of the ginning and carding rates on the area shrinkages of the T-shirts produced from the matching fiber groups.

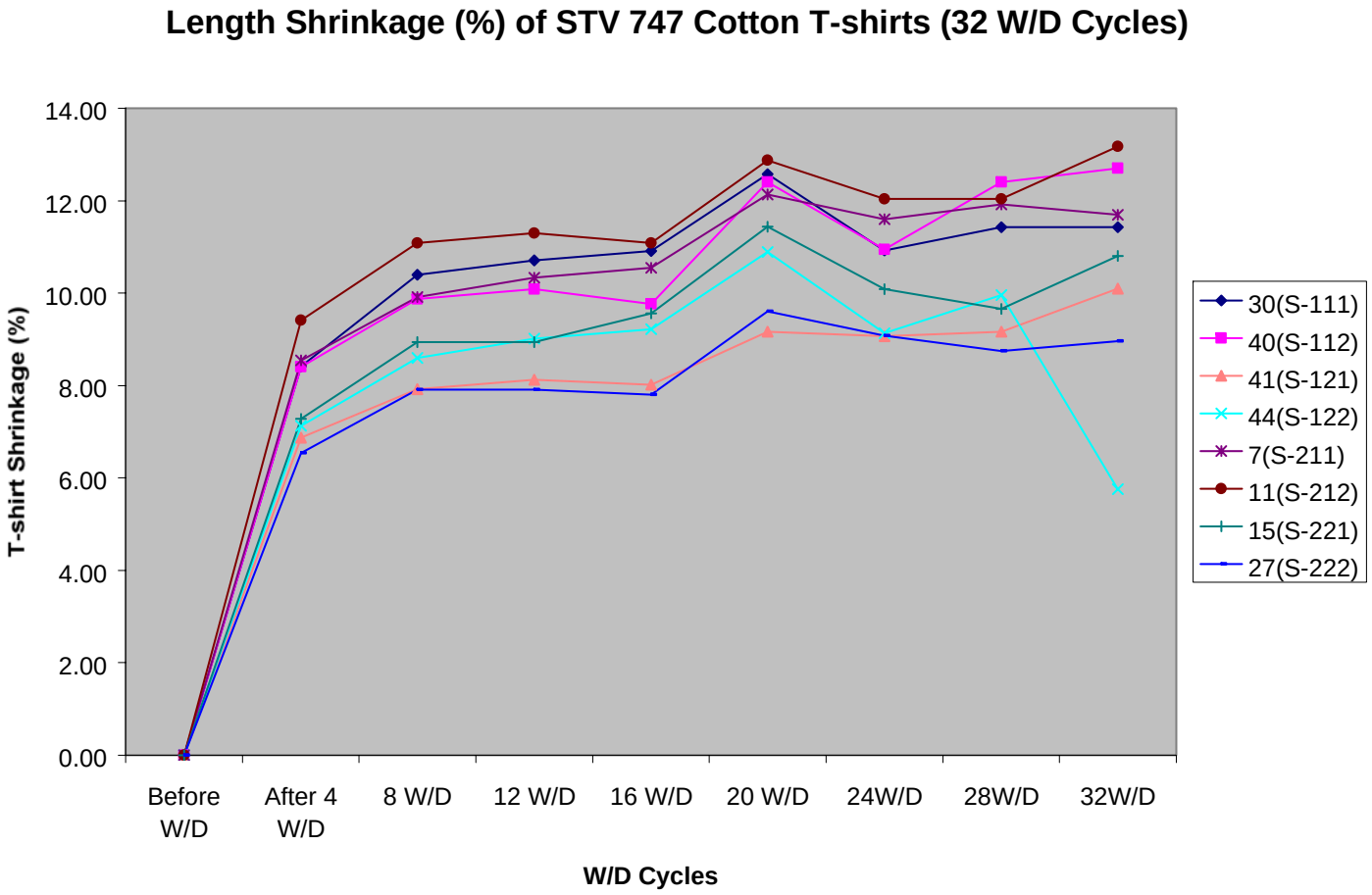

Figure 30. Length Shrinkage (%) after 32 W/D cycles for STV 747 T-shirts

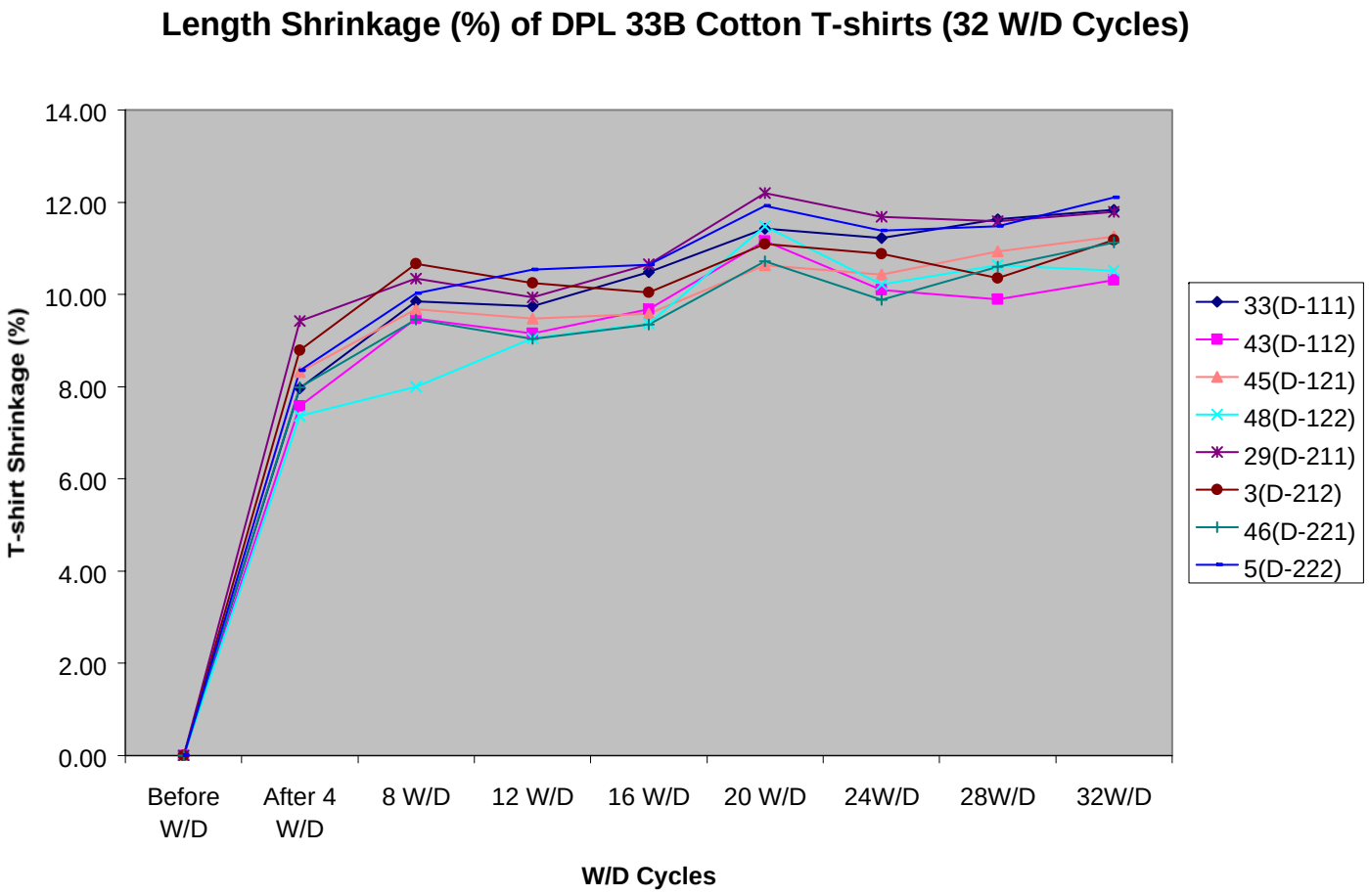

Figure 31. Length Shrinkage (%) after 32 W/D cycles for DPL 33B T-shirts

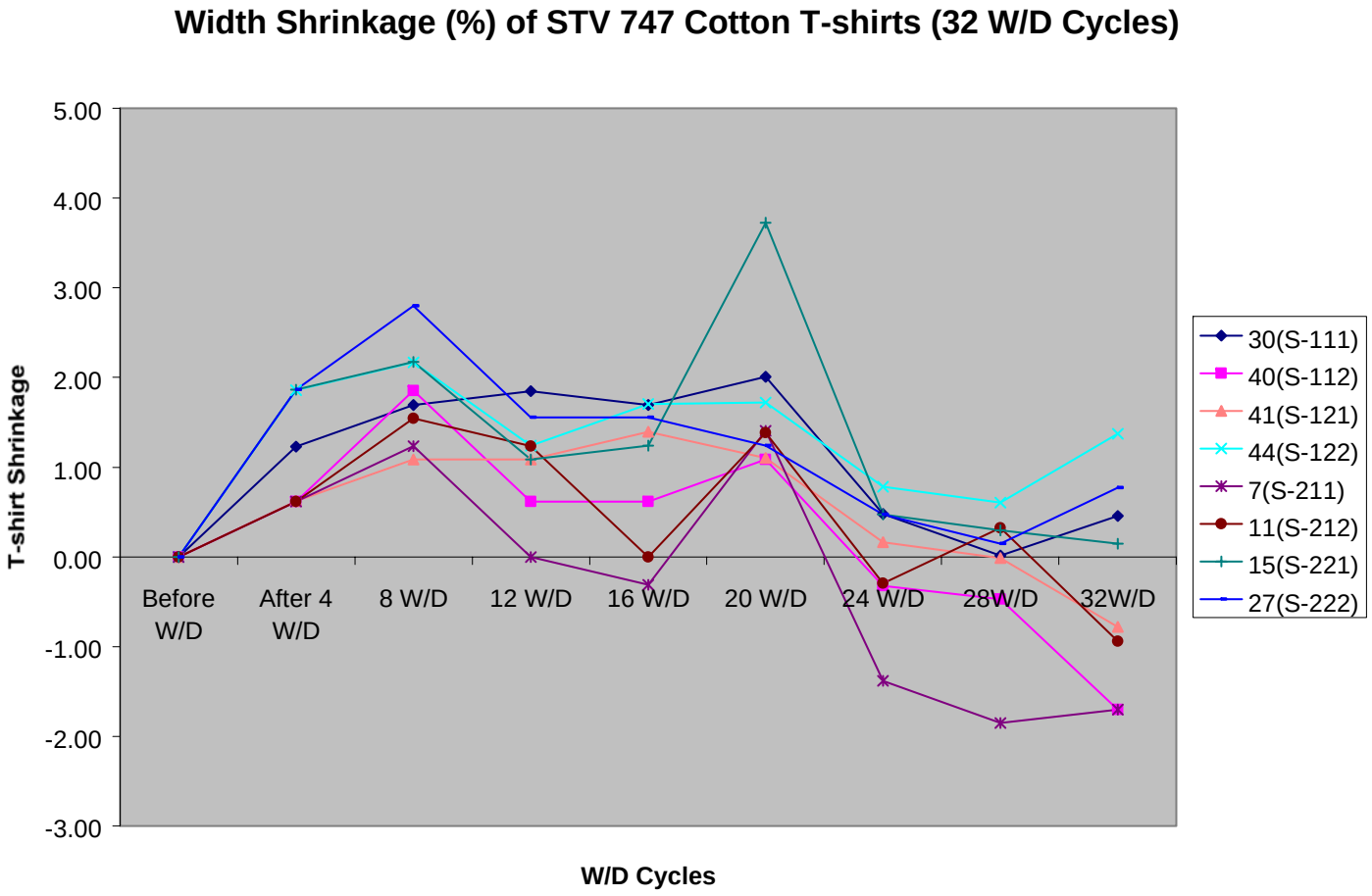

Figure 32. Width Shrinkage (%) after 32 W/D cycles for STV 747 T-shirts

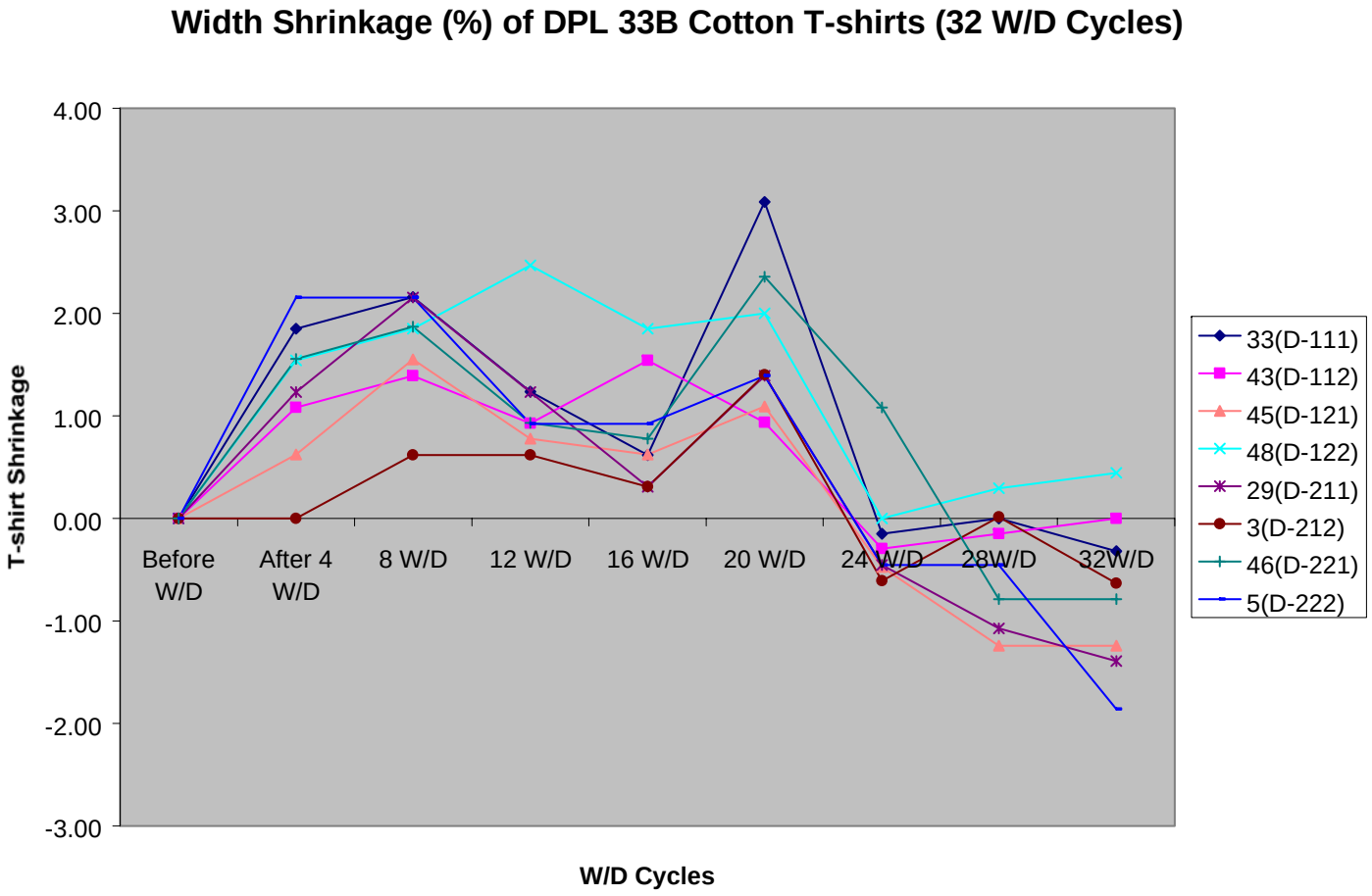

Figure 33. Width Shrinkage (%) after 32 W/D cycles for DPL 33B T-shirts

Table 22. Length Shrinkages of Washed STV 747 T-shirts Corresponding to the Processing Conditions of the Constituent Fiber (After 32 W/D Cycles)

Ginning Rate	No. of Lint Cleaners	Carding Rate	Lenth Shrinkage (%)
1	1	1	11.1
1	1	1	11.8
1	1	2	13.3
1	1	2	12.1
1	2	1	9.6
1	2	1	10.6
1	2	2	10.9
1	2	2	10.7
2	1	1	11.6
2	1	1	11.8
2	1	2	13.4
2	1	2	12.9
2	2	1	11.4
2	2	1	10.2
2	2	2	10.1
2	2	2	7.8

Table 23. Width Shrinkages of Washed STV 747 T-shirts Corresponding to the Processing Conditions of the Constituent Fiber (After 32 W/D Cycles)

Ginning Rate	No. of Lint Cleaners	Carding Rate	Width Shrinkage (%)
1	1	1	0.3
1	1	1	0.6
1	1	2	-0.9
1	1	2	-2.5
1	2	1	0.0
1	2	1	-1.6
1	2	2	1.2
1	2	2	1.5
2	1	1	-1.2
2	1	1	-2.2
2	1	2	-0.6
2	1	2	-1.3
2	2	1	-0.7
2	2	1	0.9
2	2	2	1.2
2	2	2	0.9

Tables 24 and 25 show the area shrinkages of the washed T-shirts made of DPL 33B and STV 747 T cottons, respectively, processed under various conditions. Based on this data, the average area shrinkages were calculated for each of the processing factors. For STV 747 T-shirts, the area shrinkage was higher with the high ginning rate. It was also higher with 1 lint cleaner, and with low carding rate. For DPL 33B T-shirts, the area shrinkage was higher with the low ginning rate, 1 lint cleaners, and low carding rate. These results are shown in Tables 26 – 31.

Table 24. Area Shrinkages of Washed STV 747 T-shirts Corresponding to the Processing Conditions of the Constituent Fiber (After 32 W/D Cycles)

Ginning Rate	No. of Lint Cleaners	Carding Rate	Area Shrinkage (%)
1	1	1	11.3
1	1	1	12.3
1	1	2	12.5
1	1	2	9.9
1	2	1	9.5
1	2	1	9.2
1	2	2	11.9
1	2	2	12.1
2	1	1	10.5
2	1	1	9.9
2	1	2	12.9
2	1	2	11.8
2	2	1	10.8
2	2	1	11.0
2	2	2	11.2
2	2	2	8.1

Table 25. Area Shrinkages of Washed DPL 33B T-shirts Corresponding to the Processing Conditions of the Constituent Fibers (After 32 W/D Cycles)

Ginning Rate	No. of Lint Cleaners	Carding Rate	Area Shrinkage (%)
1	1	1	12.0
1	1	1	11.1
1	1	2	10.3
1	1	2	10.3
1	2	1	10.1
1	2	1	10.2
1	2	2	10.4
1	2	2	11.5
2	1	1	10.7
2	1	1	10.5
2	1	2	12.5
2	1	2	8.7
2	2	1	9.6
2	2	1	11.3
2	2	2	11.2
2	2	2	8.7

Table 26. Summary Statistics for Area Shrinkages of STV 747 T-shirts Based on the Ginning Rate

Ginning Rate	No. of Tests	Area Shrinkage (%)			
		Mean	Std Dev.	Min.	Max.
Low	8	11.11	1.34	9.25	12.52
High	8	10.78	1.40	8.13	12.91

Table 27. Summary Statistics for Area Shrinkages of STV 747 T-shirts Based on the Number of Lint Cleaners

No. of Lint Cleaners	No. of Tests	Area Shrinkage (%)			
		Mean	Std Dev.	Min.	Max.
1	8	11.40	1.19	9.80	12.90
2	8	10.50	1.39	8.13	12.09

Table 28. Summary Statistics for Area Shrinkages of STV 747 T-shirts Based on the Carding Rate

Carding Rate	No. of Tests	Area Shrinkage (%)			
		Mean	Std Dev.	Min.	Max.
Low	8	10.59	1.01	9.25	12.31
High	8	11.31	1.58	8.13	12.91

Table 29. Summary Statistics for Area Shrinkages of DPL 33B T-shirts Based on the Ginning Rate

Ginning Rate	No. of Tests	Area Shrinkage (%)			
		Mean	Std Dev.	Min.	Max.
Low	8	10.73	0.70	10.11	11.97
High	8	10.39	1.33	8.70	12.50

Table 30. Summary Statistics for Area Shrinkages of DPL 33B T-shirts Based on the Number of Lint Cleaners

No. of Lint Cleaners	No. of Tests	Area Shrinkage (%)			
		Mean	Std Dev.	Min.	Max.
1	8	10.76	1.16	8.70	12.50
2	8	10.36	0.95	8.70	11.47

Table 31. Summary Statistics for Area Shrinkages of DPL 33B T-shirts Based on the Carding Rate

Carding Rate	No. of Tests	Area Shrinkage (%)			
		Mean	Std Dev.	Min.	Max.
Low	8	10.68	0.76	9.56	11.97
High	8	10.44	1.31	8.70	12.50

Statistical analyses were made based on these data. The ANOVA tables for both STV 747 and DPL 33B T-shirts are shown in Tables 32 and 33.

Table 32. ANOVA for Processing Effects on Area Shrinkage of STV 747 T-shirts Undergone 32 Repeated W/D

GLM Procedure

Class Level Information

Class	Levels	Values
Gin	2	1 2
Lint	2	1 2
Card	2	1 2

Number of observation 16

Dependent Variable: Breaking Elongation (%)

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	5.72594298	1.90864766	1.09	0.3899
Error	12	20.96944441	1.74745370		
Corrected Total	15	26.69538740			

Root MSE	1.321913	R-square	0.214492
Dependent Mean	10.94851	Coeff Var	12.07391

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Gin	1	0.42893187	0.42893187	0.25	0.6292
Lint	1	3.20932358	3.20932358	1.84	0.2003
Card	1	2.08768754	2.08768754	1.19	0.2958

Table 33. ANOVA for Processing Effects on Area Shrinkage of DPL 33B T-shirts Undergone 32 Repeated W/D

GLM Procedure

Class Level Information

Class	Levels	Values
Gin	2	1 2
Lint	2	1 2
Card	2	1 2

Number of observation 16

Dependent Variable: Breaking Elongation (%)

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	1.37228267	0.45742756	0.37	0.7774
Error	12	14.91147902	1.24262325		
Corrected Total	15	16.28376170			

Root MSE	1.114730	R-square	0.084273
Dependent Mean	10.55938	Coeff Var	10.55678

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Gin	1	0.48151386	0.48151386	0.39	0.5453
Lint	1	0.66497990	0.66497990	0.54	0.4785
Card	1	0.22578890	0.22578890	0.18	0.6775

As seen clearly in Tables 32 and 33, there were no significant effects of processing conditions on the area shrinkages of T-shirts.

At this point, we must recognize the limitations of our washing/drying experiments. Even though we normally assume that the repeated washing and drying experiment simulate the actual wear tests accompanied by wash and wear cycles, we also know that it is only a crude approximation at best. In a real situation, the garment worn by a person undergoes many repeated stretch and recovery cycles in the dry state. Therefore, a systemic loading and unloading cycles might be added

between any two successive washing/drying cycles in order to better simulate the real wash and wear environment. In addition, it may be possible to study the tensile and other properties of the fabrics as found in garment in relation with the effects of the processing conditions.

5.6 Study of Fiber Morphology by a Scanning Electron Microscope

The efforts have been made to study the surface properties of cotton based on the STV 747 cotton fibers pulled from T-shirts at the end of 32 cycles of washing and drying. The observations are limited and cannot provide a general conclusion on the effects of ginning and carding methods. However, the observable differences may generate new research hypotheses on the structural damage of cotton due to mechanical processing. Because of the time and expense limitations, the study samples were drawn from 3 T-shirts showing the largest and smallest length shrinkages and one in-between without considering the processing conditions. The results, however, turned out to be as follows:

	Gin	No. of Lint Cleaner	Card
Low Shrinkage T-shirts:	High	2	High
Medium Shrinkage T-shirts:	High	2	Low
High Shrinkage T-shirts:	High	1	High

While the samples were not drawn for estimating the processing effects, it is clear that the differences, if any, in the surface properties can be attributed to the effects of carding rate and the number of lint cleaners.

5.6.1 Results and Discussion

For the low shrinkage T-shirt (LST), the fiber surfaces are shown in Figure 34 and Figure 35. In general, it appears that individual fibers from LST showed many cracks and broken fibrils compared to the other two T-shirts. As this particular T-shirt was made from the most severe processing conditions (high ginning and high carding, two lint cleaners in ginning), it is quite tempting to say that damage to cotton fibers is quite significant under the harsh processing conditions.

For the medium shrinkage T-shirts (MST), Figure 36 and Figure 37 seem to show somewhat less fibrillar fragmentation and less crack in the fibers. Comparing MST to LST, the only difference was in the lower carding rate for MST. Again, it is plausible to argue that the improved look in the fiber surfaces of MST is due to the low rate of carding. The number of samples and the qualitative assessment, however, may not justify to draw a general conclusion.

The high shrinkage T-shirt (HST), Figure 38 and Figure 39, show by far the best surface morphology. The fibrillar fragments are fewer and the cracks in fibers seem much less compared to MST and LST. Comparing HST to LST, the difference is clearly due to the one lint cleaner ginning for HST. On the other hand, the difference between HST and MST is due to both number of lint cleaners and carding rate. While the two effects are confounded, it is quite clear that the favorable effects in HST would have been even more magnified had the MST been from cotton process at high carding rate. That is, the single lint

cleaner in HST is perhaps the most important factor in minimizing the damage to cotton fibers in spite of the high carding rate associated with HST.

As stated earlier, these observations are useful but preliminary as the sample sizes and the assessment method have not been rigorous. Nevertheless, the differences detected from the limited amount of work seem to justify the conventional belief that high speed cotton processing and excessive cleaning impart irreversible damage to cotton fibers as manifested also by the tensile properties of single cotton fibers examined in this study.

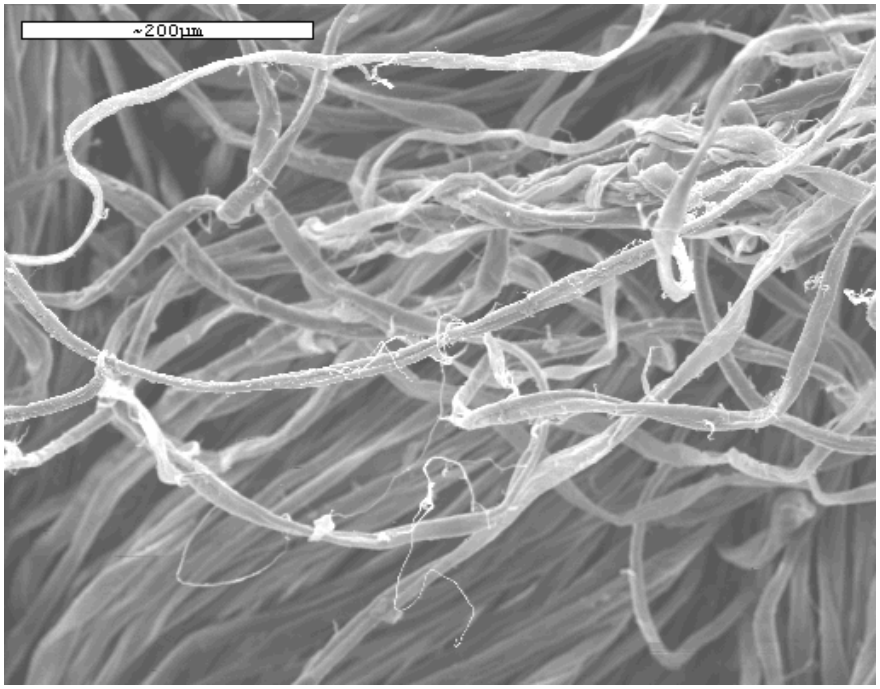

Figure 34. Fibers on the Surface of T-shirt with Low Shrinkage (× 300)

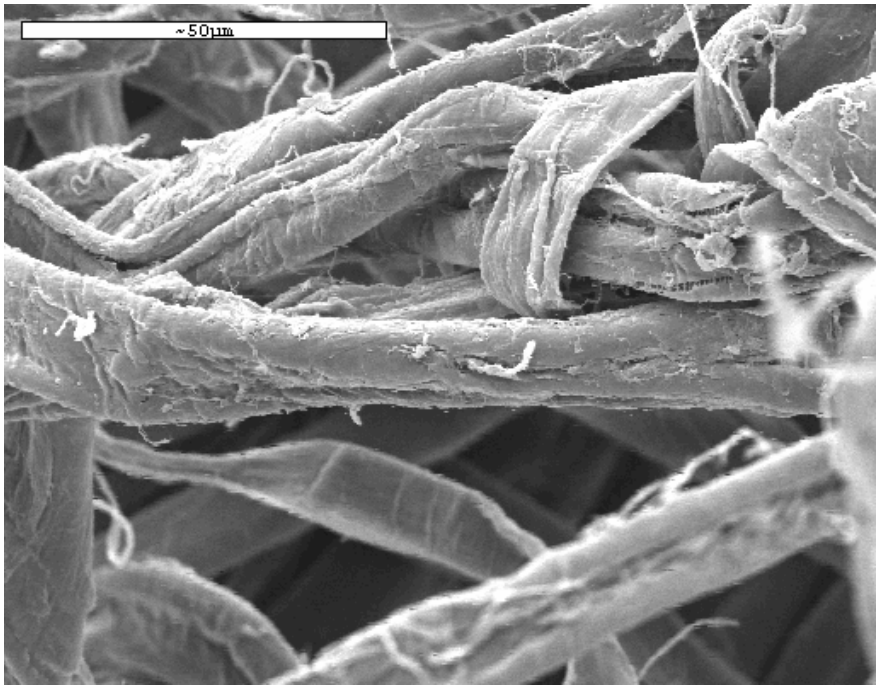

Figure 35. Fibers on the Surface of T-shirt with Low Shrinkage (× 1500)

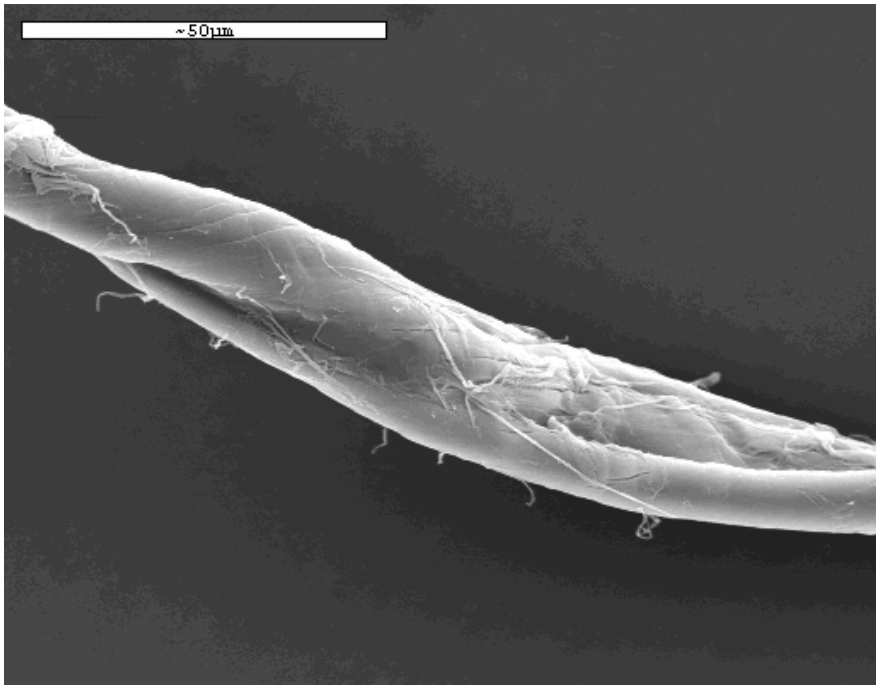

Figure 36. Fiber on the Surface of T-shirt with Medium Shrinkage (× 1500)

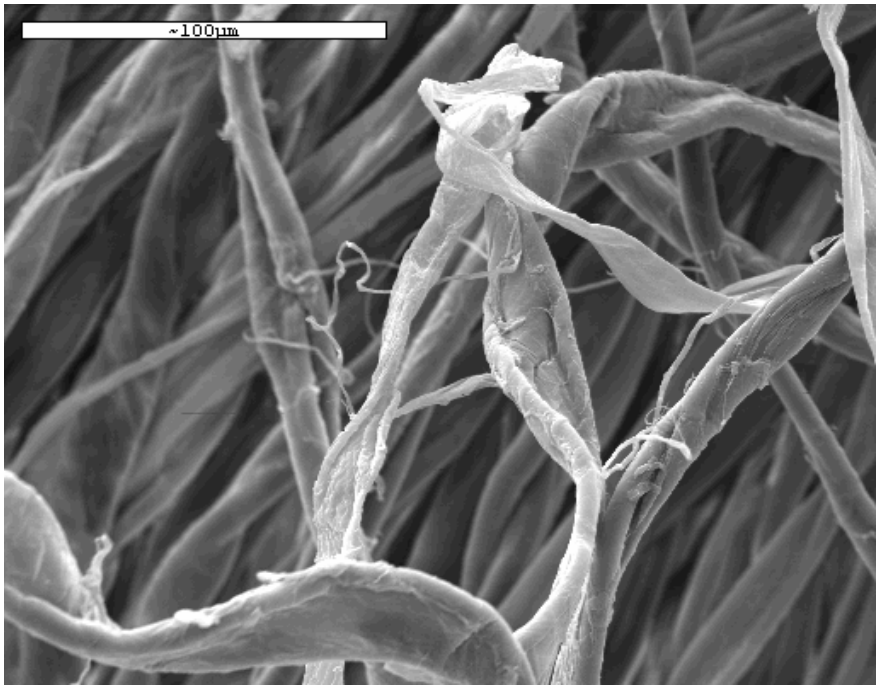

Figure 37. Fibers on the Surface of T-shirt with Medium Shrinkage (× 3000)

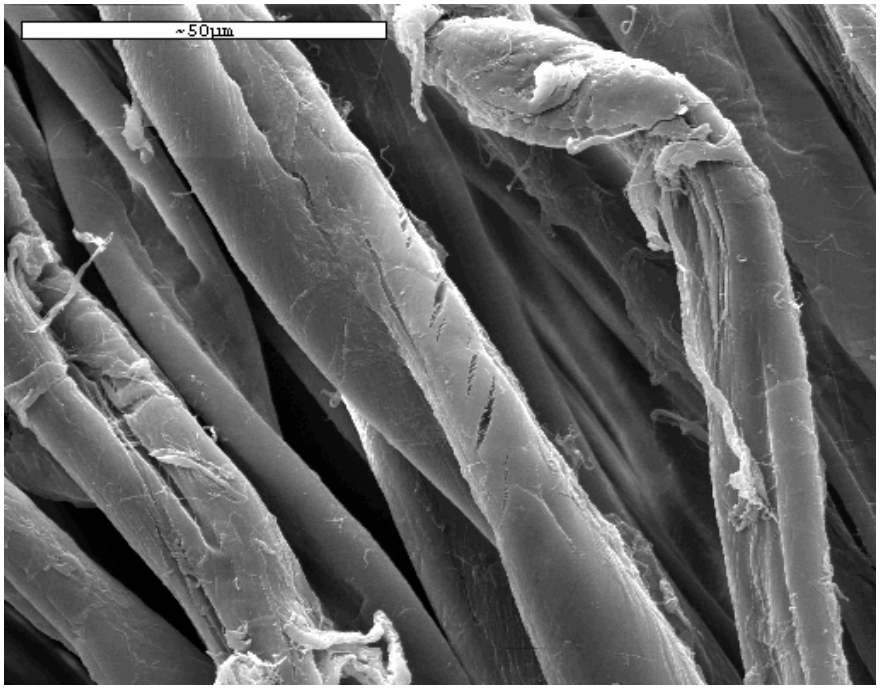

Figure 38. Fibers on the Surface of T-shirt with High Shrinkage (× 1500)

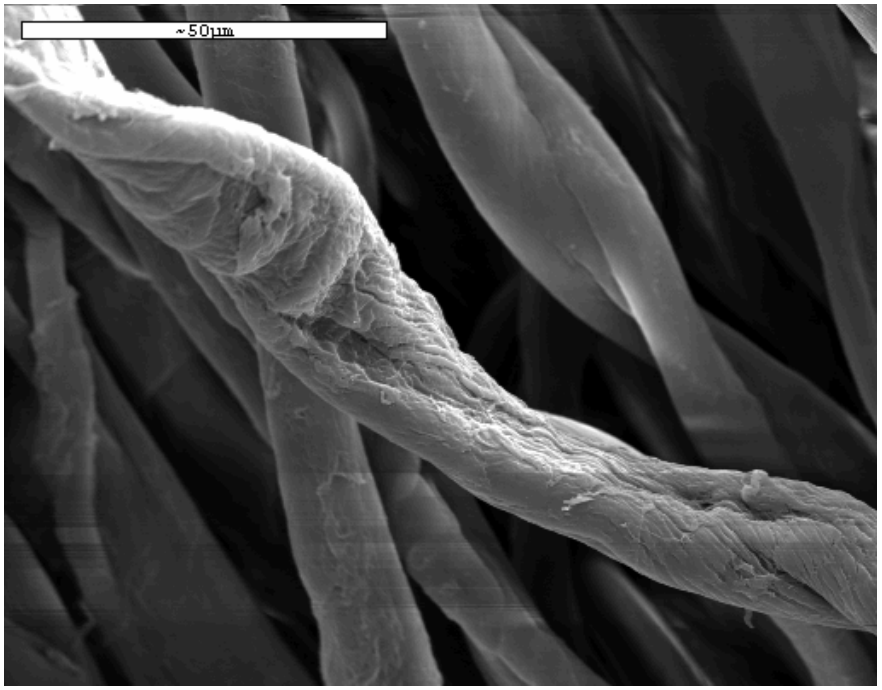

Figure 39. Fibers on the Surface of T-shirt with High Shrinkage (× 1500)

6 CONCLUSIONS

A) Based on roughly 21,200 Mantis® single fiber tests performed on cotton fiber samples taken from raw cotton all the way to washed/dried garments, a definitive proof has been established that the average tensile strength, average breaking elongation and the average work to break are continuously reduced as the processing steps are added. The pattern of the changes, however, is extremely complex in terms of the processing methods and processing variables involved.

B) Ginning causes tensile degradation. Contrary to the conventional expectation, however, the decrease in the average breaking strength of a ginned cotton fiber was less when it was ginned at a higher rate than that from a lower rate. The high ginning rate, however, resulted in low average breaking elongation of a fiber than the low ginning rate.

C) Ginning with two lint cleaners produced a lower average breaking strength and a lower average breaking elongation than that with one lint cleaner.

D) Carding also produces tensile degradation in cotton fibers. Unlike the effects of ginning rate, however, the higher carding rate generated a lower average breaking strength than the lower carding rate. The higher carding rate also produced a lower breaking elongation.

E) A possible model was proposed to explain how the tensile strength of a cotton fiber is realized by equating the strength of a fiber to the strength of a two-component bundle consisting of inner and outer fibrillar layers although the number of layers are many in reality. The new model does not provide a

quantitative projection of fiber strength but only a method of explaining what could happen within a fiber when the fiber is subjected to processing.

F) Cotton fibers tested after wet processing exhibited marked reduction in the average fiber strengths with the higher rate of ginning and the higher rate of carding. This may suggest that the ultimate effects of processing may not be fully demonstrated before the fibers are fully relaxed through wet processing.

G) The average breaking strength and breaking elongation showed the marked reductions when the fibers were tested after wet processing. The reduction, however, represent not only the effects of wet processing but also the effects of all dry processes following carding (drawing, roving, spinning, winding and knitting). These effects were not studied separately in this research.

H) The progressive length shrinkage of the T-shirts during 32 washing/drying cycles was shown to be consistently higher for the higher ginning and carding rates. The progressive width and area shrinkage on the other hand did not show the effects of processing clearly.

I) A limited microscopic study suggests that the number of lint cleaners in ginning may be the most significant contributor to fiber damage as shown by the broken fibrils and cracks on fiber surfaces. Although it is not conclusive, the evidence also suggests that higher ginning and carding rates, or the harsher processing conditions in general, are detrimental to surface properties of cotton fibers.

7 RECOMMENDATIONS FOR FUTURE WORK

In spite of the large number of Mantis® single fiber test performed at various stages of processing, the differences in ginning rates and carding rates were perhaps not large enough to show the effects of ginning and carding rates. For this reason, an experiment with maximum attainable limits of processing should be a desirable step. In addition, the ginned and carded samples may have to be blended uniformly before tests although the blending may further damage the cotton. The effects of processing after carding may be studied by testing fiber samples at the end of each process. This, however, was not the objective of this study.

In order to study the performance of cotton in garments, it would be highly desirable to combine the repeated washing and drying with repeated wear trials in between. Other forms of garment/fabric performance, such as shape retention and elastic recovery capabilities, should also be studied. Finally, the gap between the tensile properties of fibers and that of fabrics must be understood better in order to design an enhanced experiment in the future.

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9 APPENDIX

A. Possible Model for Strength of Cotton Fibers

As stated in 5.4, the tensile response of cotton fibers to axial loading is rather complex when multi-layer structure of a cotton fiber is assumed. However, the mechanical response to axial loading can be simplified by a two-layer model, namely, the inner layer and the outer layer. While the analysis is for a two-layer structure, the results can be generalized easily to a multi-layer case.

The mechanical behavior of cotton fibers would be quite different at different stages of processing as the tensile responses of inner and outer fibrillar layers are different at different loading conditions. Two schematic models were developed and shown in Figures 40 and 41 by varying the load - extension curves of the inner and outer layers within a fiber

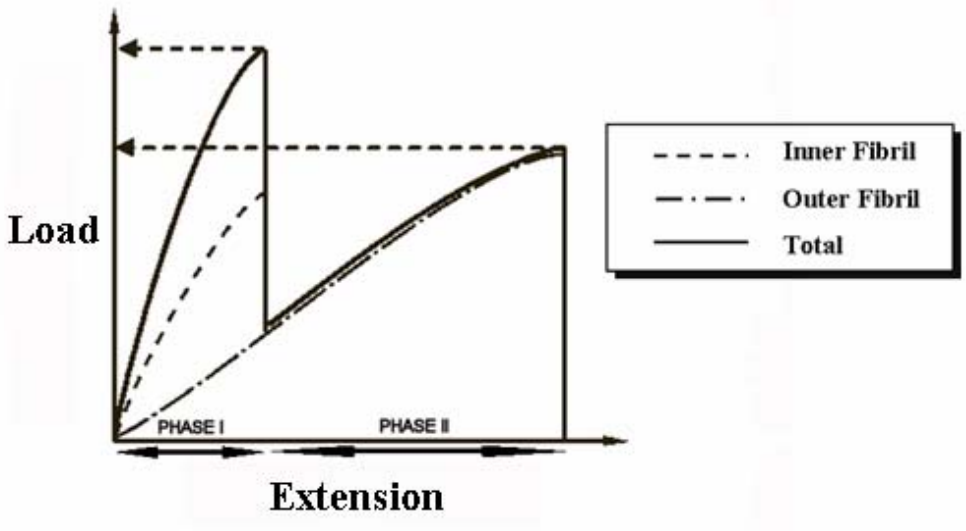


Figure 40. Theoretical Load-Extension Curve - Case I: the Maximum Strength Realized at the Breaking Extension of Inner Fibrils

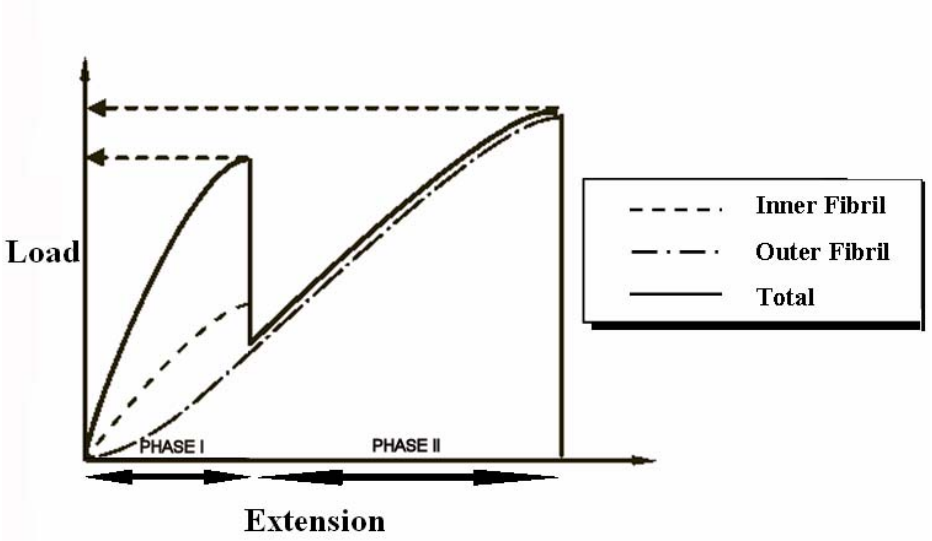


Figure 41. Theoretical Load-Extension Curve - Case II: the Maximum Strength Realized at the Breaking Extension of Outer Fibrils

In Figure 40, the maximum breaking strength is realized at the breaking extension point of the inner fibrillar layer. The maximum breaking strength is the peak load obtainable by adding the two load components of the inner and outer layers.

In Figure 41, the maximum breaking load is realized solely by the breaking strength of the outer fibrillar layer as the contribution by the inner layer was not sufficient to provide a maximum load at its breakage point.

In addition to the above two cases of tensile responses of a fiber, the changes in this responses as the process continues should be also considered. It is critical to know whether the inner fibrillar layer is damaged or broken at which processing stage.

Based on the above diagrams, cotton fiber could be in two different phases during processing. As a fiber undergoes a certain process, the fibrillar angles of inner and outer layers decrease up to the breaking point of the inner layer (Phase I in

Figures 40 and 41). Between the breaking point of the inner layer and the outer layer, the fiber is in Phase II in Figures 40 and 41. In this phase, the breaking strength of cotton fiber has decreased while the fiber is not broken yet. During dry processing, which is from ginning up to before finishing, the fibers do not have the relaxation step. With this reason, extended fibers could not have chance to recover their original property of elongation. Consequently, as the process continues, the extensibility of the fibers could be reduced.

After the wet processing, the tensile responses of fibers would be more complicated compared to the responses during dry process. Although the finishing and scouring would damage the fiber significantly, the relaxation procedure is expected to give resiliency to the fibers, resulting in more extensibility. If the fiber is in Phase I, in which both the inner and outer layer still exist, the breaking strength of fiber would be affected by the inner layer. However, if the fiber is in Phase II, the tensile behavior of the fiber would be decided by that of the outer layer, solely.

Therefore, it is critical for their tensile properties whether the fiber is in Phase I or II during the dry process in order to understand the changes in the tensile properties of a fiber during the processing.

A-1. Proportion of Inner and Outer Fibrils in a Cotton Fiber – A Theoretical Evaluation

Without considering the possible differences in the micro-structures of inner and outer fibrils, one may assume that their angles and weight proportions play key

roles in determining the tensile responses of the fiber as a whole. There is no way to find out the right proportion of inner fibrillar layer in a fiber. In our research the number of layer in a fiber was restricted only as two. However, utilizing this restriction should still give us insight about the inner and outer layers and their contributions to the fibers' tensile behavior. With this reason, various proportions of inner-outer fibrils were studied and referred in the following sections. In Hearle's study [49], the elongations and the strengths of cotton fibers were calculated by the use of spiral angle of fibrils θ, bulk modulus K_f, fiber Young's modulus E_f, and Poisson's ratio σ. In this research, we applied his model to the inner-outer fibrillar model for the estimation of the proportion of inner and outer fibrils in a fiber.

Previous researchers [70-75] stated that the fibrillar angles of cotton fibers are estimated to be around 20°~30°. Therefore, we set the angle of the inner layer to be 25°, and outer layer 30° for the discrimination the behaviors of two different layers. There was no specific reference describing the breaking elongations of these layers. However, from our cotton test data, we assumed that the breaking elongations of inner and outer layers were set to 10% and 15%, respectively. Hearle also proposed two models. One was with constant helix angle, a Young's modulus of fiber at 2300 kg/mm^2 and a bulk modulus greater than about 1000 kg/mm^2, which was comparable to the value for a wholly crystalline solid. The other was a model with the same Young's modulus, but a bulk modulus of only about 100kg/mm^2, which is comparable to the value for liquids or a soft rubber

[31]. After comparing of his theoretical model to experimental data by Spark *et al.* [82] and Stout *et al.* [83], Hearle concluded that the bulk modulus should be at least 1000 kg/mm^2 to get a good agreement with the experiment. Therefore, in this study we applied Young's modulus of 2300 kg/mm^2, and bulk modulus of 5000 kg/mm^2 to estimate the appropriate proportions of inner and outer fibrillar layers. The stresses of inner layer f_i and outer layer f_o are given by the equation:

$$f_{i(o)} = E_f \varepsilon_{i(o)} (\cos^2 \theta_{i(o)} - \sigma_{i(o)} \sin^2 \theta_{i(o)})^2 + K_f \varepsilon_{i(o)} (1 - 2\sigma_{i(o)})^2 \quad (9)$$

$$\sigma_{i(o)} = \frac{E_f \cos^2 \theta_{i(o)} \sin^2 \theta_{i(o)} + 2K_f}{E_f \sin^4 \theta_{i(o)} + 4K_f} \quad (10)$$

where,

$fi(o)$ = stress of a inner (outer) fibrillar layer

E_f = fiber Young's modulus (kg/mm^2)

K_f = bulk modulus (kg/mm^2)

$\sigma_i(o)$ = Poisson's ratio of a inner (outer) fibrillar layer

$\varepsilon_i(o)$ = elongation of a inner (outer) fibrillar layer

$\theta_i(o)$ = fibrillar angle of a inner (outer) layer (°)

The total stress of a cotton fiber is given by the linear summation of the stresses of inner and outer fibrillar layer.

$$f = f_i + f_o \quad (11)$$

From Equations 9- 11, the following plots are made.

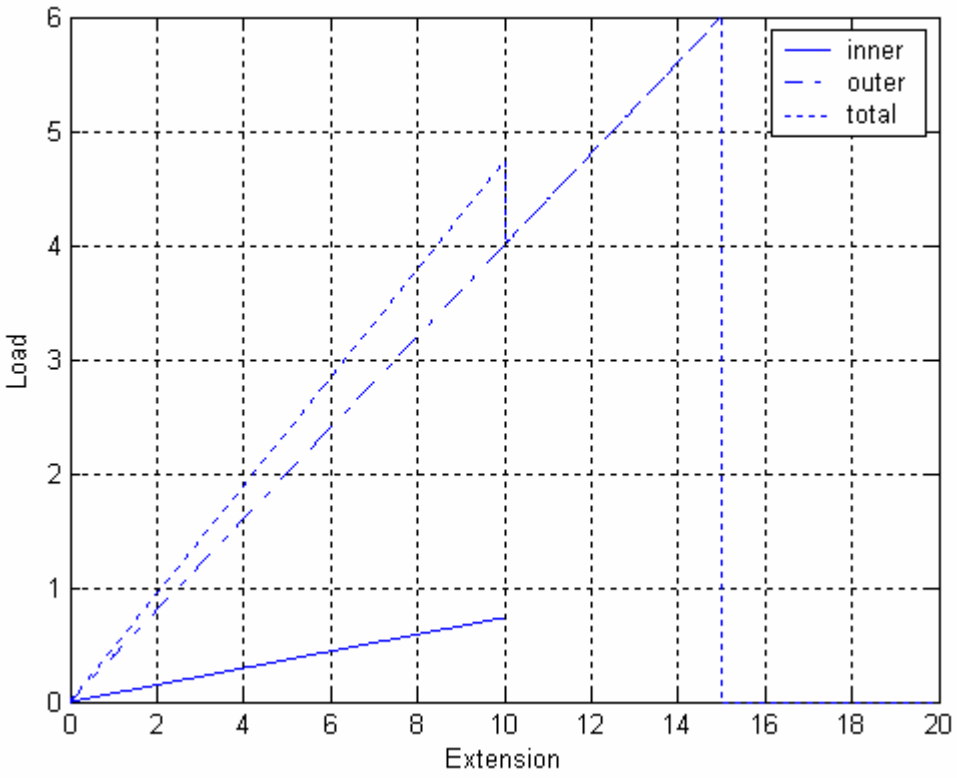


Figure 42. Load-Extension Curve for Cotton Fiber: Volume Ratio of Inner and Outer Fibril = 10:90

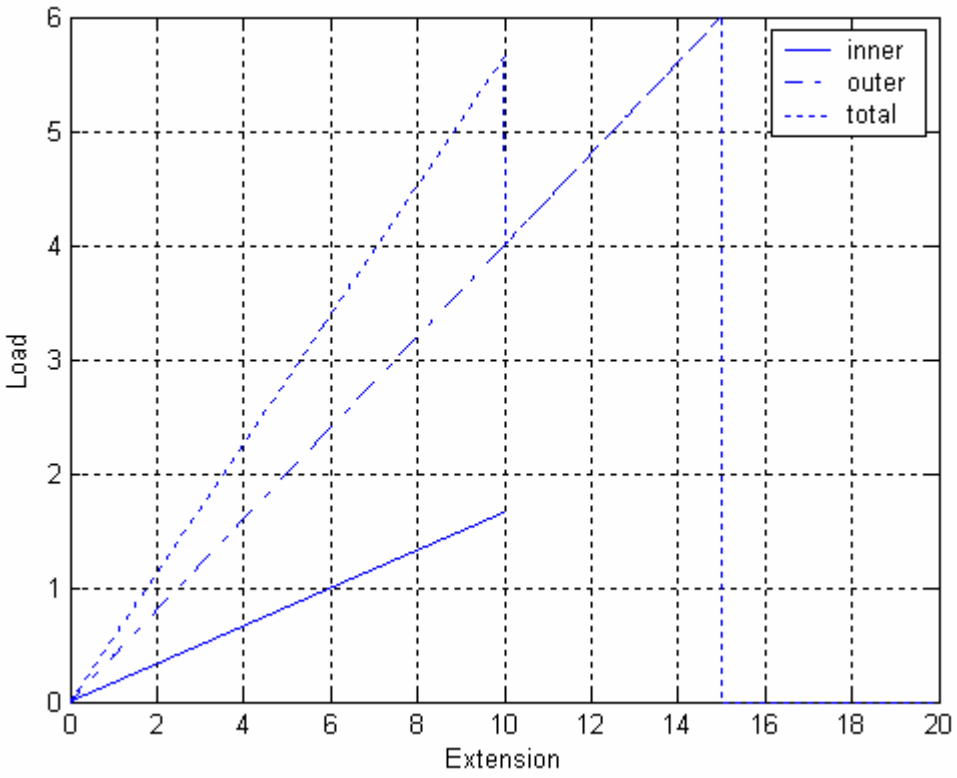


Figure 43. Load-Extension Curve for Cotton Fiber: Volume Ratio of Inner and Outer Fibril = 20:80

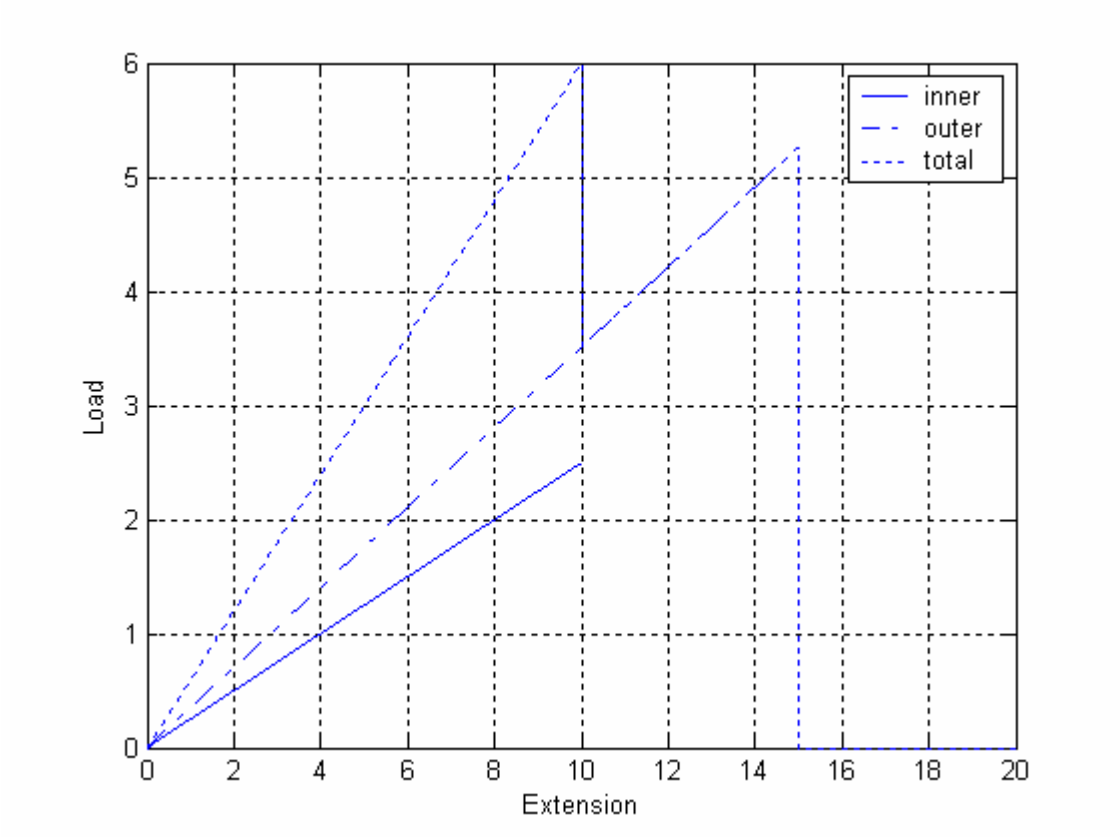


Figure 44. Load-Extension Curve for Cotton Fiber: Volume Ratio of Inner and Outer Fibril = 30:70

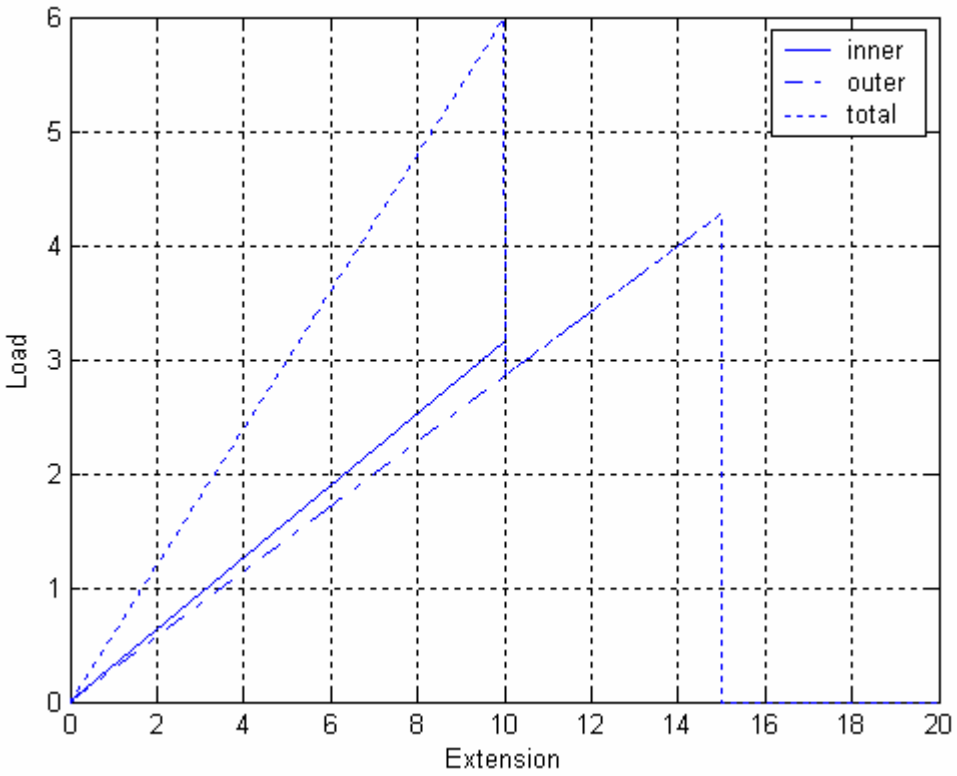


Figure 45. Load-Extension Curve for Cotton Fiber: Volume Ratio of Inner and Outer Fibril = 40:60

Figures 42 – 45 show load – extension curves of a cotton fiber with various ratios of inner and outer fibrillar layers. At ratios of 10:90 and 20:80 (Figures 42 and 43), the breakage of outer fibrillar layer determined the fiber breaking strength. When the inner fibrils continuously increased (Figures 4444 and 45), however, the breaking strength of the fiber was determined by summation of the breaking strength of inner fibrils and the strength of outer fibrils.

There were some limitations in the above modeling. Although the fiber Young's modulus is well established value, the bulk modulus K_f has not been fixed at a constant value by the previous researches. Therefore, an attempt has been made here to examine the tensile response, a fiber to the changes in bulk modulus and

the proportions of inner and outer fibrillar layers. By varying the bulk modulus K_f from 1000 kg/mm^2 to 5000 kg/mm^2, the resulting stresses of a cotton fiber was calculated by the Equations 9 to 11 at different ratios of inner and outer layers. For this, the breaking elongations of the inner layer and the outer layer were set to 10% and 15%, respectively, as before. The response surface is shown in Figure 46.

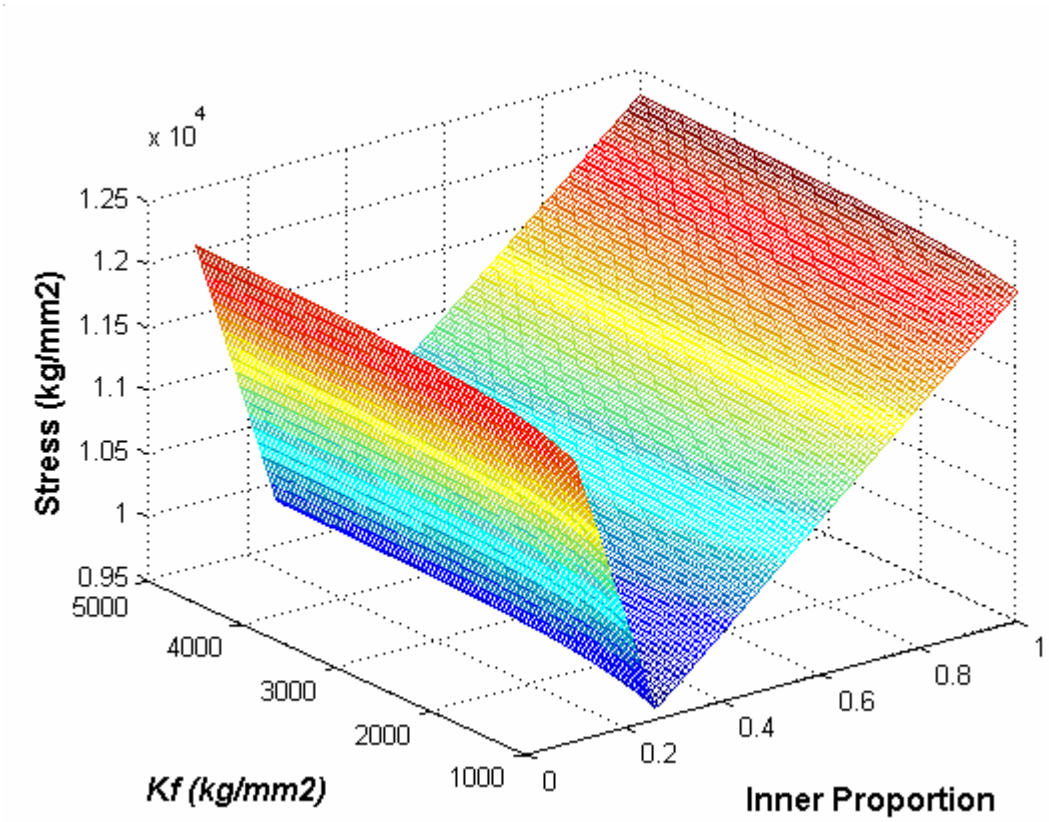


Figure 46. Breaking Stress vs. Bulk Modulus and the Proportion of Inner Layer

As the bulk modulus increased from 1000 kg/mm^2 to 5000 kg/mm^2, the resulting load on the fiber was shown to increase only slightly regardless of the proportion of the inner layer. From 1000kg/mm^2 to about 2800kg/mm^2, the stress increased slightly but the increase became insignificant beyond that point. From 0 to about 0.27 of the inner proportion of a fiber, the stress decreased significantly, and

beyond the point it began to increase linearly. The phase change occurred between 20:80 (Figure 41) and 30:70 (Figure 40). Based on this in-depth analysis, it is found that the changes in K_f increased from 1000 kg/mm^2 to 5000 kg/mm^2 generates negligible changes in fiber stress whereas the changes in the ratio of inner layer produce large differences.

The above model and discussion of experimental results are based on the two-layer model of cotton fibers. The analogy is trivial for a multi-layer cases except the combination of different mechanical behaviors of different layers have to be considered.

What is important is the fact that the commonly expected effects of high/low processing rates on tensile properties of cotton fibers may or may not be realized in view of the model proposed here. Needless to say, a higher processing rate can indeed increase the breaking strength of cotton fibers although such an observation cannot be generalized.

B. SAS analysis output for the effects of processing conditions on the tensile properties of STV 747 fibers from card slivers

The SAS System 16:08 Thursday, July 10, 2003 1

gin=1 lint=1 card=1

The MEANS Procedure

Variable	N	Mean	Std Dev	Minimum	Maximum
bs	2400	6.6184667	2.3915764	0.4700000	17.0100000
be	2400	19.8532333	7.6965532	0.1800000	54.8800000

gin=1 lint=1 card=2

Variable	N	Mean	Std Dev	Minimum	Maximum
bs	2799	6.3206324	2.4077503	0.5900000	89.8700000
be	2799	19.6562272	7.8763458	-8.0900000	55.9400000

gin=1 lint=2 card=1

Variable	N	Mean	Std Dev	Minimum	Maximum
bs	2400	6.4498500	2.4238120	0.5300000	16.7500000
be	2400	20.5621167	7.7974956	0.1100000	52.0900000

gin=1 lint=2 card=2

Variable	N	Mean	Std Dev	Minimum	Maximum
bs	2800	6.4422393	2.3903581	0.4500000	15.3100000
be	2800	19.9950071	7.8988802	-0.5400000	60.7000000

gin=2 lint=1 card=1

Variable	N	Mean	Std Dev	Minimum	Maximum
bs	3200	6.5407938	2.3873887	0.4700000	15.7500000
be	3200	21.3377969	8.1931755	0.1700000	53.3400000

---------- gin=2 lint=1 card=2 ----------

The MEANS Procedure

Variable	N	Mean	Std Dev	Minimum	Maximum
bs	3200	6.6444406	2.5915806	0.4500000	36.9600000
be	3200	20.5009250	8.2162530	-0.4500000	62.1200000

---------- gin=2 lint=2 card=1 ----------

Variable	N	Mean	Std Dev	Minimum	Maximum
bs	2800	6.7193786	2.5258313	0.4600000	16.2900000
be	2800	20.1426786	7.9367284	-0.5700000	53.5800000

---------- gin=2 lint=2 card=2 ----------

Variable	N	Mean	Std Dev	Minimum	Maximum
bs	3200	6.3837094	2.3927183	0.4700000	16.9400000
be	3200	20.7377031	7.9772255	-0.1400000	61.9600000

The GLM Procedure

Dependent Variable: bs

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	7	384.4515	54.9231	9.21	<.0001
Error	22791	135919.1434	5.9637		
Corrected Total	22798	136303.6049			

R-Square	Coeff Var	Root MSE	bs Mean
0.002821	37.48590	2.442073	6.514644

Source	DF	Type I SS	Mean Square	F Value	Pr > F
gin	1	75.4617016	75.4617016	12.66	0.0004
lint	1	6.6477731	6.6477731	1.11	0.2911
card	1	94.1700840	94.1700840	15.79	<.0001
gin*lint	1	1.7697343	1.7697343	0.30	0.5859
gin*card	1	2.7288916	2.7288916	0.46	0.4988
lint*card	1	16.1798690	16.1798690	2.71	0.0995
gin*lint*card	1	187.5084712	187.5084712	31.44	<.0001

Source	DF	Type III SS	Mean Square	F Value	Pr > F
gin	1	73.5806699	73.5805699	12.36	0.0004
lint	1	5.9142931	5.9142931	0.99	0.3193
card	1	101.4406777	101.4406777	17.01	<.0001
gin*lint	1	0.4220743	0.4220743	0.07	0.7902
gin*card	1	1.8708521	1.8708521	0.31	0.5754
lint*card	1	7.7680161	7.7680161	1.30	0.2538
gin*lint*card	1	187.5084712	187.5084712	31.44	<.0001

The GLM Procedure

Dependent Variable: be

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	7	6176.359	882.337	13.90	<.0001
Error	22791	1446466.496	63.467		
Corrected Total	22798	1452642.854			

R-Square	Coeff Var	Root MSE	be Mean
0.004252	39.09015	7.966691	20.38005

Source	DF	Type I SS	Mean Square	F Value	Pr > F
gin	1	2732.832683	2732.832683	43.06	<.0001
lint	1	1.674971	1.674971	0.03	0.8709
card	1	387.444736	387.444736	6.10	0.0135
gin*lint	1	1303.476281	1303.476281	20.54	<.0001
gin*card	1	78.728633	78.728633	1.24	0.2654
lint*card	1	529.781482	529.781482	8.35	0.0039
gin*lint*card	1	1142.420289	1142.420289	18.00	<.0001

Source	DF	Type III SS	Mean Square	F Value	Pr > F
gin	1	2475.332155	2475.332155	39.00	<.0001
lint	1	2.807008	2.807008	0.04	0.8334
card	1	356.024910	356.024910	5.61	0.0179
gin*lint	1	1416.727776	1416.727776	22.31	<.0001
gin*card	1	96.962988	96.962988	1.51	0.2188
lint*card	1	396.639660	396.639660	6.25	0.0124
gin*lint*card	1	1142.420289	1142.420289	18.00	<.0001

The GLM Procedure

Dependent Variable: bs

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	5	201.6869	40.3374	6.75	<.0001
Error	22793	136102.0180	5.9712		
Corrected Total	22798	136303.6049			

R-Square	Coeff Var	Root MSE	bs Mean
0.001479	37.50947	2.443608	6.514644

Source	DF	Type I SS	Mean Square	F Value	Pr > F
gin	1	75.46170146	75.46170146	12.64	0.0004
lint	1	6.64777314	6.64777314	1.11	0.2914
card	1	94.17008406	94.17008406	15.77	<.0001
lint*card*gin	2	25.30730994	12.65365497	2.12	0.1202

Source	DF	Type III SS	Mean Square	F Value	Pr > F
gin	1	41.16366450	41.16365450	6.89	0.0087
lint	1	9.95641378	9.95641378	1.67	0.1966
card	1	0.65592209	0.65592209	0.11	0.7403
lint*card*gin	2	25.30730994	12.65365497	2.12	0.1202

The GLM Procedure

Dependent Variable: be

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	5	3803.856	760.771	11.97	<.0001
Error	22793	1448838.998	63.565		
Corrected Total	22798	1452642.854			

R-Square	Coeff Var	Root MSE	be Mean
0.002619	39.12048	7.972772	20.38005

Source	DF	Type I SS	Mean Square	F Value	Pr > F
gin	1	2732.832683	2732.832683	42.99	<.0001
lint	1	1.674971	1.674971	0.03	0.8710
card	1	387.444736	387.444736	6.10	0.0136
lint*card*gin	2	681.903406	340.951703	5.36	0.0047

Source	DF	Type III SS	Mean Square	F Value	Pr > F
gin	1	1047.536080	1047.536080	16.48	<.0001
lint	1	503.625952	503.625952	7.92	0.0049
card	1	803.164382	803.164382	12.64	0.0004
lint*card*gin	2	681.903406	340.951703	5.36	0.0047

C. SAS analysis output for the effects of processing conditions on the tensile properties of DPL 33B fibers from card slivers

The MEANS Procedure

gin	lint	card	N Obs	Variable	Label	N	Mean	Std Dev	Minimum	Maximum
1	1	1	2800	str	F1	2800	5.5623357	2.5527004	0.4700000	19.5300000
				elo	F2	2800	14.9522536	6.5272781	-0.0600000	43.9300000
				work	F3	2800	13.6837500	9.9990098	-0.0100000	66.2000000
		2	2800	str	F1	2800	5.6485714	2.6395777	0.4600000	18.9900000
				elo	F2	2800	15.2229107	6.6915331	-0.0100000	46.7300000
				work	F3	2800	14.5025429	10.9551250	0	87.1300000
	2	1	2400	str	F1	2400	5.9012458	2.6280673	0.4400000	15.4400000
				elo	F2	2400	15.6959917	6.4797405	-0.1400000	48.6500000
				work	F3	2400	15.0452500	10.9061565	-0.0300000	90.3100000
		2	2797	str	F1	2797	6.1019128	2.6390225	0.5200000	19.6400000
				elo	F2	2797	16.6222095	7.2131454	0.0600000	48.6300000
				work	F3	2797	16.8699249	12.1634657	0.0100000	82.1000000
2	1	1	2800	str	F1	2800	5.8714500	2.7259855	0.5000000	17.0300000
				elo	F2	2800	15.4110929	6.6068216	-0.1200000	61.2700000
				work	F3	2800	14.7842464	10.9484340	-0.2000000	122.4600000
		2	3200	str	F1	3200	5.9646312	2.4703059	0.4200000	14.6900000
				elo	F2	3200	16.0539000	6.5767131	0.0900000	44.3100000
				work	F3	3200	15.4500000	10.6364011	0	108.1800000
	2	1	2800	str	F1	2800	5.9076786	2.6612733	0.4600000	16.2700000
				elo	F2	2800	15.8431107	6.7329800	0.0100000	63.5500000
				work	F3	2800	15.3691893	10.9365779	0	71.6500000
		2	2800	str	F1	2800	5.7087893	2.6578924	0.4200000	17.1000000
				elo	F2	2800	15.0257964	6.6047773	-0.3600000	43.0800000
				work	F3	2800	14.3156179	10.6337313	-0.0300000	73.6800000

C-1. Breaking Strength

The GLM Procedure

Dependent Variable: str F1

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	6	574.6315	95.7719	13.67	<.0001
Error	22390	156821.2012	7.0041		
Corrected Total	22396	157395.8327			

R-Square	Coeff Var	Root MSE	str Mean
0.003651	45.36046	2.646521	5.834423

Source	DF	Type I SS	Mean Square	F Value	Pr > F
gin	1	24.9711320	24.9711320	3.57	0.0590
lint	1	103.6582136	103.6582136	14.80	0.0001
card	1	15.2714417	15.2714417	2.18	0.1398
gin*lint	1	367.6571773	367.6571773	52.52	<.0001
gin*card	1	49.9643389	49.9643389	7.13	0.0076
lint*card	1	12.9091781	12.9091781	1.84	0.1746

Source	DF	Type III SS	Mean Square	F Value	Pr > F
gin	1	19.4614981	19.4614981	2.78	0.0955
lint	1	114.9825879	114.9825879	16.42	<.0001
card	1	11.1593662	11.1593662	1.59	0.2069
gin*lint	1	367.3529180	367.3529180	52.45	<.0001
gin*card	1	49.7608542	49.7608542	7.10	0.0077
lint*card	1	12.9091781	12.9091781	1.84	0.1746

C-2. Breaking Elongation

The GLM Procedure

Dependent Variable: elo F2

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	6	5727.363	954.561	21.33	<.0001
Error	22390	1002181.880	44.760		
Corrected Total	22396	1007909.243			

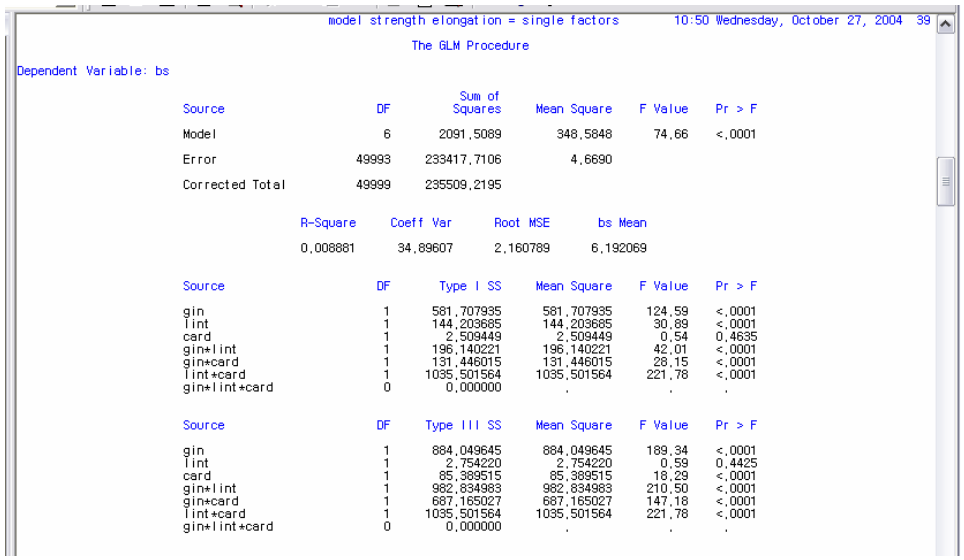
R-Square	Coeff Var	Root MSE	elo Mean
0.005682	42.79158	6.690310	15.63464

Source	DF	Type I SS	Mean Square	F Value	Pr > F
gin	1	29.382250	29.382250	0.66	0.4178
lint	1	986.223459	986.223459	22.03	<.0001
card	1	580.996874	580.996874	12.98	0.0003
gin*lint	1	3191.560524	3191.560524	71.30	<.0001
gin*card	1	773.785210	773.785210	17.29	<.0001
lint*card	1	165.415078	165.415078	3.70	0.0546

Source	DF	Type III SS	Mean Square	F Value	Pr > F
gin	1	47.959206	47.959206	1.07	0.3006
lint	1	1076.759126	1076.759126	24.06	<.0001
card	1	509.776773	509.776773	11.39	0.0007
gin*lint	1	3185.206749	3185.206749	71.16	<.0001
gin*card	1	770.917344	770.917344	17.22	<.0001
lint*card	1	165.415078	165.415078	3.70	0.0546

D. SAS analysis output for the effects of processing conditions on the tensile properties of STV 747 fibers from unwashed T-shirts

D-1. Breaking Strength



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The GLM Procedure

Dependent Variable: bs

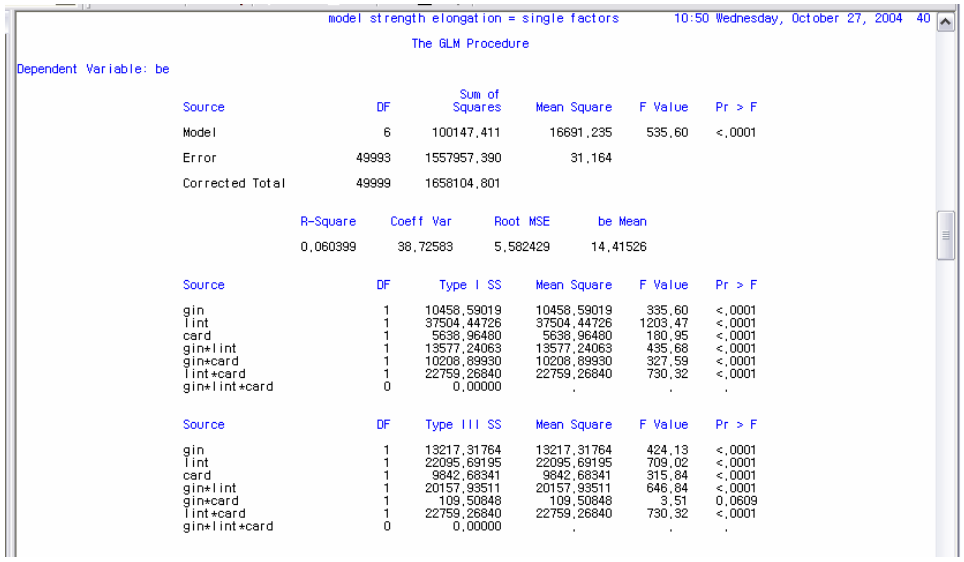
Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	6	2091,5089	348,5848	74,66	<,0001
Error	49993	233417,7106	4,6690		
Corrected Total	49999	235509,2195			

R-Square	Coeff Var	Root MSE	bs Mean
0,008881	34,89607	2,160789	6,192069

Source	DF	Type I SS	Mean Square	F Value	Pr > F
gin	1	581,707935	581,707935	124,59	<,0001
lint	1	144,203685	144,203685	30,89	<,0001
card	1	2,509449	2,509449	0,54	0,4635
gin*lint	1	196,140221	196,140221	42,01	<,0001
gin*card	1	131,446015	131,446015	28,15	<,0001
lint*card	1	1035,501564	1035,501564	221,78	<,0001
gin*lint*card	0	0,000000	.	.	.

Source	DF	Type III SS	Mean Square	F Value	Pr > F
gin	1	884,049645	884,049645	189,34	<,0001
lint	1	2,754220	2,754220	0,59	0,4425
card	1	85,389515	85,389515	18,29	<,0001
gin*lint	1	982,834983	982,834983	210,50	<,0001
gin*card	1	687,165027	687,165027	147,18	<,0001
lint*card	1	1035,501564	1035,501564	221,78	<,0001
gin*lint*card	0	0,000000	.	.	.

D-2. Breaking Elongation



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The GLM Procedure

Dependent Variable: be

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	6	100147,411	16691,235	535,60	<,0001
Error	49993	1557957,390	31,164		
Corrected Total	49999	1658104,801			

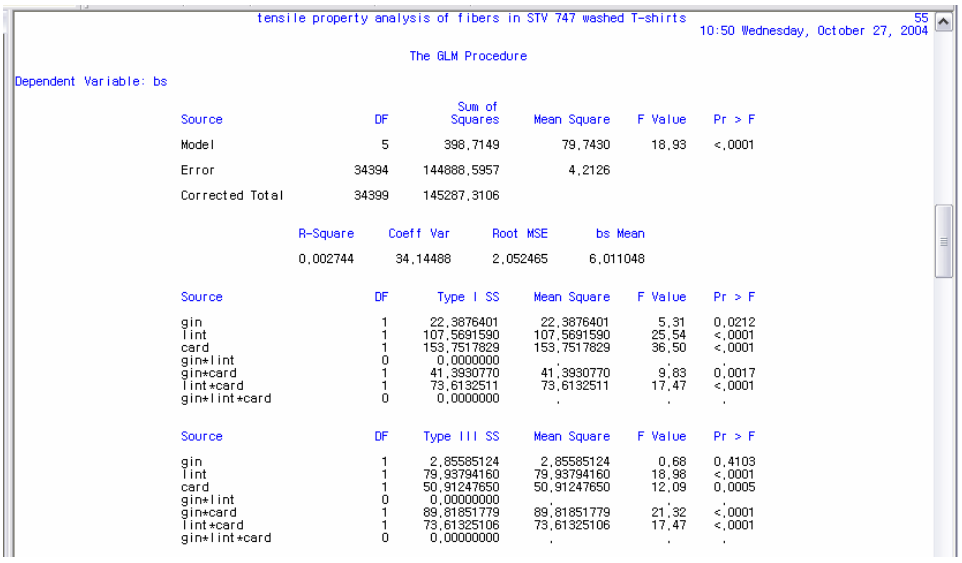
R-Square	Coeff Var	Root MSE	be Mean
0,060399	38,72583	5,582429	14,41526

Source	DF	Type I SS	Mean Square	F Value	Pr > F
gin	1	10458,59019	10458,59019	335,60	<,0001
lint	1	37504,44726	37504,44726	1203,47	<,0001
card	1	5638,96480	5638,96480	180,95	<,0001
gin*lint	1	13577,24063	13577,24063	435,68	<,0001
gin*card	1	10208,89930	10208,89930	327,59	<,0001
lint*card	1	22759,26840	22759,26840	730,32	<,0001
gin*lint*card	0	0,00000	.	.	.

Source	DF	Type III SS	Mean Square	F Value	Pr > F
gin	1	13217,31764	13217,31764	424,13	<,0001
lint	1	22095,69195	22095,69195	709,02	<,0001
card	1	9842,68341	9842,68341	315,84	<,0001
gin*lint	1	20157,93511	20157,93511	646,84	<,0001
gin*card	1	109,50848	109,50848	3,51	0,0609
lint*card	1	22759,26840	22759,26840	730,32	<,0001
gin*lint*card	0	0,00000	.	.	.

E. SAS analysis output for the effects of processing conditions on the tensile properties of STV 747 fibers from unwashed T-shirts

E-1. Breaking Strength



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The GLM Procedure

Dependent Variable: bs

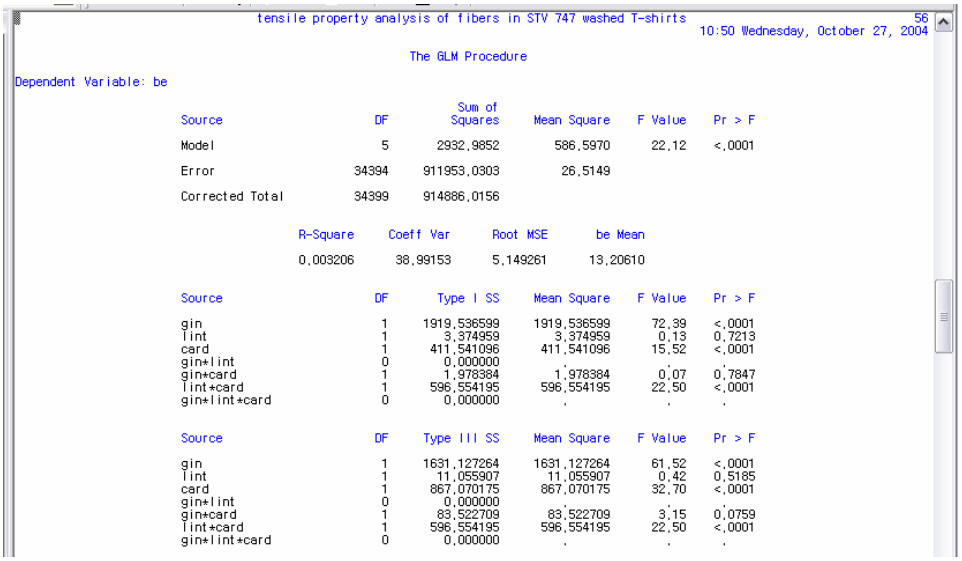
Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	5	398,7149	79,7430	18,93	<,0001
Error	34394	144888,5957	4,2126		
Corrected Total	34399	145287,3106			

R-Square	Coeff Var	Root MSE	bs Mean
0,002744	34,14488	2,052465	6,011048

Source	DF	Type I SS	Mean Square	F Value	Pr > F
gin	1	22,3876401	22,3876401	5,31	0,0212
lint	1	107,5691590	107,5691590	25,54	<,0001
card	1	153,7517829	153,7517829	36,50	<,0001
gin*lint	0	0,0000000	.	.	.
gin*card	1	41,3930770	41,3930770	9,83	0,0017
lint*card	1	73,6132511	73,6132511	17,47	<,0001
gin*lint*card	0	0,0000000	.	.	.

Source	DF	Type III SS	Mean Square	F Value	Pr > F
gin	1	2,85585124	2,85585124	0,68	0,4103
lint	1	79,93794160	79,93794160	18,98	<,0001
card	1	50,91247650	50,91247650	12,09	0,0005
gin*lint	0	0,00000000	.	.	.
gin*card	1	89,81851779	89,81851779	21,32	<,0001
lint*card	1	73,61325106	73,61325106	17,47	<,0001
gin*lint*card	0	0,00000000	.	.	.

E-2. Breaking Elongation



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The GLM Procedure

Dependent Variable: be

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	5	2932,9852	586,5970	22,12	<,0001
Error	34394	911953,0303	26,5149		
Corrected Total	34399	914886,0156			

R-Square	Coeff Var	Root MSE	be Mean
0,003206	38,99153	5,149261	13,20610

Source	DF	Type I SS	Mean Square	F Value	Pr > F
gin	1	1919,536599	1919,536599	72,39	<,0001
lint	1	3,374959	3,374959	0,13	0,7213
card	1	411,541096	411,541096	15,52	<,0001
gin*lint	0	0,000000	.	.	.
gin*card	1	1,978384	1,978384	0,07	0,7847
lint*card	1	596,554195	596,554195	22,50	<,0001
gin*lint*card	0	0,000000	.	.	.

Source	DF	Type III SS	Mean Square	F Value	Pr > F
gin	1	1631,127264	1631,127264	61,52	<,0001
lint	1	11,055907	11,055907	0,42	0,5185
card	1	867,070175	867,070175	32,70	<,0001
gin*lint	0	0,000000	.	.	.
gin*card	1	83,522709	83,522709	3,15	0,0759
lint*card	1	596,554195	596,554195	22,50	<,0001
gin*lint*card	0	0,000000	.	.	.

F. SAS analysis output for the effects of processing conditions on the shrinkage properties of STV 747 fibers from card slivers

F-1. Length Shrinkage

The SAS System
Effects of processing conditions on the length of washed STV T-shirts

The GLM Procedure

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	18.07757090	6.02585697	5.57	0.0125
Error	12	12.97968719	1.08164060		
Corrected Total	15	31.05725809			

R-Square	Coeff Var	Root MSE	lsh Mean
0.582072	9.281341	1.040020	11.20549

Source	DF	Type I SS	Mean Square	F Value	Pr > F
gin	1	0.03784732	0.03784732	0.03	0.8547
lint	1	17.39831379	17.39831379	16.09	0.0017
card	1	0.64140979	0.64140979	0.59	0.4562

Source	DF	Type III SS	Mean Square	F Value	Pr > F
gin	1	0.03784732	0.03784732	0.03	0.8547
lint	1	17.39831379	17.39831379	16.09	0.0017
card	1	0.64140979	0.64140979	0.59	0.4562

F-2. Width Shrinkage

The GLM Procedure

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	8.98455803	2.99485268	2.32	0.1267
Error	12	15.46643660	1.28886972		
Corrected Total	15	24.45099463			

R-Square	Coeff Var	Root MSE	lsh Mean
0.367452	-436.6452	1.135284	-0.260001

Source	DF	Type I SS	Mean Square	F Value	Pr > F
gin	1	0.14292673	0.14292673	0.11	0.7449
lint	1	8.11583732	8.11583732	6.30	0.0274
card	1	0.72579397	0.72579397	0.56	0.4675

Source	DF	Type III SS	Mean Square	F Value	Pr > F
gin	1	0.14292673	0.14292673	0.11	0.7449
lint	1	8.11583732	8.11583732	6.30	0.0274
card	1	0.72579397	0.72579397	0.56	0.4675

G. Matlab® program code for calculating maximum strength for a cotton fiber with various inner-outer ratios.

```
function [f]=inout3070(epsilon1,epsilon2,theta,Ef,Kf)
% epsilon1:  0<epsilon1<epsilon2 with stepsize 0.01
% epsilon2:  0<epsilon2<20 with stepsize 0.01
% theta : [theta1*180/pi,theta2*180/pi]

sigma1=(Ef*((cos(theta(1)))^2)*((sin(theta(1)))^2)+2*Kf)/(Ef*(sin(theta(1)))^4+4*Kf);
f1=0.3 * epsilon1*(Ef*(((cos(theta(1)))^2)-sigma1*((sin(theta(1)))^2))^2+Kf*(1-2*sigma1)^2);


sigma2=(Ef*((cos(theta(2)))^2)*((sin(theta(2)))^2)+2*Kf)/(Ef*(sin(theta(2)))^4+4*Kf);
f2=0.7 * epsilon2*(Ef*(((cos(theta(2)))^2)-sigma2*((sin(theta(2)))^2))^2+Kf*(1-2*sigma2)^2);



n1=length(f1);
n2=length(f2);
n3=length([0:.01:20]);
f3=zeros(1,n3);
f3(1:n1)=f1;
f4=zeros(1,n3);
f4(1:n2)=f2;

f4=f4+f3;
Max_f4=max(f4)/6;
f1=f1/Max_f4;
f2=f2/Max_f4;
f4=f4/Max_f4;
plot(epsilon1,f1);hold on;grid on;
plot(epsilon2,f2,'-.');
plot([0:.01:20],f4,':');
legend('inner','outer','total');
%title('aaa');

hold off;
f1=f1';
```