IMPROVEMENTS IN COTTON FIBER PROPERTIES

COTTON FIBRE GROWTH:

Iimprovements in cotton fiber properties for textiles depend on changes in the growth and development of the fiber. Manipulation of fiber perimeter has a potential to impact the length, micronaire, and strength of cotton fibers. The perimeter of the fiber is regulated by biological mechanisms that control the expansion characteristic of the cell wall and establish cell diameter.improvements in fiber quality can take many different forms. Changes in length, strength, uniformity, and fineness In one recent analysis, fiber perimeter was shown to be the single quantitative trait of the fiber that affects all other traits . Fiber perimeter is the variable that has the greatest affect on fiber elongation and strength properties. While mature dead fibers have an elliptical morphology, living fibers have a cylindrical morphology during growth and development. Geometrically, perimeter is directly determined by diameter (perimeter = diameter × p). Thus, fiber diameter is the only variable that directly affects perimeter. For this reason, understanding the biological mechanisms that regulate fiber diameter is important for the long-term improvement of cotton.A review of the literature indicates that many researchers believe diameter is established at fiber initiation and is maintained throughout the duration of fiber development . A few studies have examined, either directly or indirectly, changes in fiber diameter during development. Some studies indicate that diameter remains constant ; while others indicate that fiber diameter increases as the fiber develops.The first three stages occur while the fiber is alive and actively growing. Fiber initiation involves the initial isodiametric expansion of the epidermal cell above the surface of the ovule. This stage may last only a day or so for each fiber. Because there are several waves of fiber initiation across the surface of the ovule , one may find fiber initials at any time during the first 5 or 6 d post anthesis. The elongation phase encompasses the major expansion growth phase of the fiber. Depending on genotype, this stage may last for several weeks post anthesis. During this stage of development the fiber deposits a thin, expandable primary cell wall composed of a variety of carbohydrate polymers . As the fiber approaches the end of elongation, the major phase of secondary wall synthesis starts. In cotton fiber, the secondary cell wall is composed almost exclusively of cellulose. During this stage, which lasts until the boll opens (50 to 60 d post anthesis), the cell wall becomes progressively thicker and the living protoplast decreases in volume. There is a significant overlap in the timing of the elongation and secondary wall synthesis stages. Thus, fibers are simultaneously elongating and depositing secondary cell wall. The establishment of fiber diameter is a complex process that is governed, to a certain extent, by the overall mechanism by which fibers expand. The expansion of fiber cells is governed by the same related mechanisms occurring in other walled plant cells. Most cells exhibit diffuse cell growth, in which new wall and membrane materials are added throughout the surface area of the cell. Specialized, highly elongated cells, such as root hairs and pollen tubes, expand via tip synthesis where new wall and membrane materials are added only at a specific location that becomes the growing tip of the cell. While the growth mechanisms for cotton fiber have not been fully documented, recent evidence indicates that throughout the initiation and early elongation phases of development, cotton fiber expands primarily via diffuse growth . Later in fiber development, late in cell elongation, and well into secondary cell wall synthesis (35 d post anthesis), the organization of cellular organelles is consistent with continued diffuse growth . Many cells that expand via diffuse growth exhibit increases in both cell length and diameter; but cells that exhibit tip synthesis do not exhibit increases in cell diameter . If cotton fiber expands by diffuse growth, then it is reasonable to suggest that cell diameter might increase during the cell elongation phase of development.Cell expansion is also regulated by the extensibility of the cell wall. For this reason, cell expansion most commonly occurs in cells that have only a primary cell wall . Primary cell walls contain low levels of cellulose. Production of the more rigid secondary cell wall usually signals the cessation of cell expansion. Secondary cell wall formation is often indicated by the development of wall birefringence.Analyses of fiber diameter and cell wall birefringence show that fiber diameter significantly increased as fibers grew and developed secondary cell walls. Both cotton species and all the genotypes tested exhibited similar increases in diameter; however, the specific rates of change differed. Fibers continued to increase in diameter during the secondary wall synthesis stage of development, indicating that the synthesis of secondary cell wall does not coincide with the cessation of cell expansion.

GINNING: The generally recommended machinery sequence at gins for spindle-picked cotton is rock and green-boll trap, feed control, tower drier, cylinder cleaner, stick machine, tower drier, cylinder cleaner, extractor feeder, gin stand, lint cleaner, lint cleaner, and press. Cylinder cleaners use rotating spiked drums that open and clean the seedcotton by scrubbing it across a grid-rod or wire mesh screen that allows the trash to sift through. The stick machine utilizes the sling-off action of channel-type saw cylinders to extract foreign matter from the seedcotton by centrifugal force. In addition to feeding seedcotton to the gin stand, the extractor feeder cleans the cotton using the stick machine's sling-off principle. In some cases the extractor-feeder is a combination of a cylinder cleaner and an extractor. Sometimes an impact or revolving screen cleaner is used in addition to the second cylinder cleaner. In the impact cleaner, seedcotton is conveyed across a series of revolving, serrated disks instead of the grid-rod or wire mesh screen. Lint cleaners at gins are mostly of the controlled-batt, saw type. In this cleaner a saw cylinder combs the fibers and extracts trash from the lint cotton by a combination of centrifugal force, scrubbing action between saw cylinder and grid bars, and gravity assisted by air current Seedcotton-type cleaners extract the large trash components from cotton. However, they have only a small influence on the cotton's grade index, visible liint foreign-matter content, and fiber length distribution when compared with the lint cleaning effects. Also, the number of neps created by the entire seedcotton cleaning process is about the same as the increase caused by one saw-cylinder lint cleaner. Most cotton gins today use one or two stages of saw-type lint cleaners. The use of too many stages of lint cleaning can reduce the market value of the bale, because the weight loss may offset any gain from grade improvement. Increasing the number of saw lint cleaners at gins, in addition to increasing the nep count and short-fiber content of the raw lint, causes problems at the spinning mill. These show up as more neps in the card web and reduced yarn strength and appearance. Pima cotton, extra-long-staple cotton, is roller ginned to preserve its length and to minimize neps. To maintain the highest possible quality bale of pima cotton, mill-type lint cleaners were for a long time the predominant cleaner used by the roller-ginning industry. Today, various combinations of impacts, incline, and pneumatic cleaners are used in most roller-ginning plants to increase lint-cleaning capacity.

COTTON FIBER QUALITY: Two simple words, fiber quality, mean quite different things to cotton growers and to cotton processors. No after-harvest mechanisms are available to either growers or processors that can improve intrinsic fiber quality.Most cotton production research by physiologists and agronomists has been directed toward improving yields, so the few cultural-input strategies suggested for improving fiber quality during the production season are of limited validity. Thus, producers have limited alternatives in production practices that might result in fibers of acceptable quality and yield without increased production costs. Fiber processors seek to acquire the highest quality cotton at the lowest price, and attempt to meet processing requirements by blending bales with different average fiber properties. Of course, bale averages for fiber properties do not describe the fiber-quality ranges that can occur within the bales or the resulting blends. Further, the natural variability among cotton fibers unpredictably reduces the processing success for blends made up of low-priced, lower-quality fibers and high-priced, higher-quality fiber. Blends that fail to meet processing specifications show marked increases in processing disruptions and product defects that cut into the profits of the yarn and textile manufacturers. Mill owners do not have sufficient knowledge of the role classing-office fiber properties play in determining the outcome of cotton spinning and dyeing processes.Even when a processor is able to make the connection between yarn and fabric defects and increased proportions of low-quality fibers, producers have no way of explaining why the rejected bales failed to meet processing specifications when the bale averages for important fiber properties fell within the acceptable ranges.

If, on the other hand, the causes of a processing defect are unknown, neither the producer nor the processor will be able to prevent or avoid that defect in the future. Any future research that is designed to predict, prevent, or avoid low-quality cotton fibers that cause processing defects in yarn and fabric must address the interface between cotton production and cotton processing.

Every bale of cotton produced in the USA crosses that interface via the USDA-AMS classing offices, which report bale averages of quantified fiber properties. Indeed, fiber-quality data reports from classing offices are designed as a common quantitative language that can be interpreted and understood by both producers and processors. But the meaning and utility of classing-office reports can vary, depending on the instrument used to evaluate.

Fiber maturity is a composite of factors, including inherent genetic fineness compared with the perimeter or cross section achieved under prevailing growing conditions and the relative fiber cell-wall thickness and the primary -to- secondary fiber cell-wall ratio, and the time elapsed between flowering and boll opening or harvest. While all the above traits are important to varying degrees in determining processing success, none of them appear in classing-office reports.

Micronaire, which is often treated as the fiber maturity measurement in classing-office data, provides an empirical composite of fiber cross section and relative wall thickening. But laydown blends that are based solely on bale-average micronaire will vary greatly in processing properties and outcomes.

Cotton physiologists who follow fiber development can discuss fiber chronological maturity in terms of days after floral anthesis. But, they must quantify the corresponding fiber physical maturity as micronaire readings for samples pooled across several plants, because valid micronaire determinations require at least 10 g of individualized fiber.

Some fiber properties, like length and single fiber strength, appear to be simple and easily understood terms. But the bale average length reported by the classing office does not describe the range or variability of fiber lengths that must be handled by the spinning equipment processing each individual fiber from the highly variable fiber population found in that bale.

Even when a processing problem can be linked directly to a substandard fiber property, surprisingly little is known about the causes of variability in fiber shape and maturity. For example:

Spinners can see the results of excessive variability in fiber length or strength when manifested as yarn breaks and production halts.Knitters and weavers can see the knots and slubs or holes that reduce the value of fabrics made from defective yarns that were spun from poor-quality fibre Inspectors of dyed fabrics can see the unacceptable color streaks and specks associated with variations in fiber maturity and the relative dye-uptake success.

The grower, ginner, and buyer can see variations in color or trash content of ginned and baled cotton.

But there are no inspectors or instruments that can see or predict any of the above quality traits of fibers while they are developing in the boll. There is no definitive reference source, model, or database to which a producer can turn for information on how cultural inputs could be adapted to the prevailing growth conditions of soil fertility, water availability, and weather (temperature, for example) to produce higher quality fiber.

The scattered research publications that address fiber quality, usually in conjunction with yield improvement, are confusing because their measurement protocols are not standardized and results are not reported in terms that are meaningful to either producers or processors. Thus, physiological and agronomic studies of fiber quality frequently widen, rather than bridge, the communication gap between cotton producers and processors.

This overview assembles and assesses current literature citations regarding the quantitation of fiber quality and the manner in which irrigation, soil fertility, weather, and cotton genetic potential interact to modulate fiber quality. The ultimate goal is to provide access to the best answers currently available to the question of what causes the annual and regional fiber quality variations

From the physiologist's perspective, the fiber quality of a specific cotton genotype is a composite of fiber shape and maturity properties that depend on complex interactions among the genetics and physiology of the plants producing the fibers and the growth environment prevailing during the cotton production season.

Fiber shape properties, particularly length and diameter, are largely dependent on genetics. Fiber maturity properties, which are dependent on deposition of photosynthate in the fiber cell wall, are more sensitive to changes in the growth environment. The effects of the growth environment on the genetic potential of a genotype modulate both shape and maturity properties to varying degrees.

Anatomically, a cotton fiber is a seed hair, a single hyperelongated cell arising from the protodermal cells of the outer integument layer of the seed coat. Like all living plant cells, developing cotton fibers respond individually to fluctuations in the macro- and microenvironments. Thus, the fibers on a single seed constitute continua of fiber length, shape, cell-wall thickness, and physical maturity .

Environmental variations within the plant canopy, among the individual plants, and within and among fields ensure that the fiber population in each boll, indeed on each seed, encompasses a broad range of fiber properties and that every bale of cotton contains a highly variable population of fibers.

Successful processing of cotton lint depends on appropriate management during and after harvest of those highly variable fiber properties that have been shown to affect finished-product quality and manufacturing efficiency . If fiber-blending strategies and subsequent spinning and dyeing processes are to be optimized for specific end-uses and profitability, production managers in textile mills need accurate and effective descriptive and predictive quantitative measures of both the means and the ranges of these highly variable fiber properties .

In the USA, the components of cotton fiber quality are usually defined as those properties reported for every bale by the classing offices of the USDA-AMS, which currently include length, length uniformity index, strength, micronaire, color as reflectance (Rd) and yellowness (+b), and trash content, all quantified by the High Volume Instrument (HVI) line. The classing offices also provide each bale with the more qualitative classers' color and leaf grades and with estimates of preparation (degree of roughness of ginned lint) and content of extraneous matter.

The naturally wide variations in fiber quality, in combination with differences in end-use requirements, result in significant variability in the value of the cotton lint to the processor. Therefore, a system of premiums and discounts has been established to denote a specified base quality. In general, cotton fiber value increases as the bulk-averaged fibers increase in whiteness (+Rd), length, strength, and micronaire; and discounts are made for both low mike (micronaire less than 3.5) and high mike (micronaire more than 4.9).

Ideal fiber-quality specifications favored by processors traditionally have been summarized thusly: "as white as snow, as long as wool, as strong as steel, as fine as silk, and as cheap as hell." These specifications are extremely difficult to incorporate into a breeding program or to set as goals for cotton producers. Fiber-classing technologies in use and being tested allow quantitation of fiber properties, improvement of standards for end-product quality, and, perhaps most importantly, creation of a fiber-quality language and system of fiber-quality measurements that can be meaningful and useful to producers and processors alike.

GENE AND ENVIRONMENTAL VARIABILITY:

Improvements in textile processing, particularly advances in spinning technology, have led to increased emphasis on breeding cotton for both improved yield and improved fiber properties Studies of gene action suggest that, within upland cotton genotypes there is little non-additive gene action in fiber length, strength, and fineness ; that is, genes determine those fiber properties. However, large interactions between combined annual environmental factors (primarily weather) and fiber strength suggest that environmental variability can prevent full realization of the fiber-quality potential of a cotton genotype.

More recently, statistical comparisons of the relative genetic and environmental influences upon fiber strength suggest that fiber strength is determined by a few major genes, rather than by variations in the growth environment . Indeed, spatial variations of single fertility factors in the edaphic environment were found to be unrelated to fiber strength and only weakly correlated with fiber length .

Genetic potential of a specific genotype is defined as the level of fiber yield or quality that could be attained under optimal growing conditions. The degree to which genetic potential is realized changes in response to environmental fluctuations such as application of water or fertilizer and the inevitable seasonal shifts such as temperature, day length, and insolation.

In addition to environment-related modulations of fiber quality at the crop and whole-plant levels, significant differences in fiber properties also can be traced to variations among the shapes and maturities of fibers on a single seed and, consequently, within a given boll.

EFFECT ON FIBER LENGTH:

Comparisons of the fiber-length arrays from different regions on a single seed have revealed that markedly different patterns in fiber length can be found in the micropylar, middle, and chalazal regions of a cotton seed - at either end and around the middle . Mean fiber lengths were shortest at the micropylar (upper, pointed end of the seed) . The most mature fibers and the fibers having the largest perimeters also were found in the micropylar region of the seed. After hand ginning, the percentage of short fibers less than 0.5 inch or 12.7 mm long on a cotton seed was extremely low.

It has been reported that, in ginned and baled cotton, the short fibers with small perimeters did not originate in the micropylar region of the seed . MEasurements of fibers from micropylar and chalazal regions of seeds revealed that the location of a seed within the boll was related to the magnitude of the differences in the properties of fibers from the micropylar and chalazal regions.

Significant variations in fiber maturity also can be related to the seed position (apical, medial, or due to the variability inherent in cotton fiber, there is no absolute value for fiber length within a genotype or within a test sample . Even on a single seed, fiber lengths vary significantly because the longer fibers occur at the chalazal (cup-shaped, lower) end of the seed and the shorter fibers are found at the micropylar (pointed) end. Coefficients of fiber-length variation, which also vary significantly from sample to sample, are on the order of 40% for upland cotton.

Variations in fiber length attributable to genotype and fiber location on the seed are modulated by factors in the micro- and macroenvironment . Environmental changes occurring around the time of floral anthesis may limit fiber initiation or retard the onset of fiber elongation. Suboptimal environmental conditions during the fiber elongation phase may decrease the rate of elongation or shorten the elongation period so that the genotypic potential for fiber length is not fully realized . Further, the results of environmental stresses and the corresponding physiological responses to the growth environment may become evident at a stage in fiber development that is offset in time from the occurrence of the stressful conditions.

Fiber lengths on individual seeds can be determined while the fibers are still attached to the seed , by hand stapling or by photoelectric measurement after ginning. Traditionally, staple lengths have been measured and reported to the nearest 32nd of an inch or to the nearest millimeter. The four upland staple classes are: short (<21>34 mm). Additionally, short fiber content is defined as the percentage of fiber less than 12.7 mm.

Cotton buyers and processors used the term staple length long before development of quantitative methods for measuring fiber properties. Consequently, staple length has never been formally defined in terms of a statistically valid length distribution.

In Fibrograph testing, fibers are randomly caught on combs, and the beard formed by the captured fibers is scanned photoelectrically from base to tip . The amount of light passing through the beard is a measure of the number of fibers that extend various distances from the combs. Data are recorded as span length (the distance spanned by a specific percentage of fibers in the test beard). Span lengths are usually reported as 2.5 and 50%. The 2.5% span length is the basis for machine settings at various stages during fiber processing.

The uniformity ratio is the ratio between the two span lengths expressed as a percentage of the longer length. The Fibrograph provides a relatively fast method for reproducibility in measuring the length and length uniformity of fiber samples. Fibrograph test data are used in research studies, in qualitative surveys such as those checking commercial staple-length classifications, and in assembling cotton bales into uniform lots.

Since 1980, USDA-AMS classing offices have relied almost entirely on high-volume instrumentation (HVI) for measuring fiber length and other fiber properties (Moore, 1996). The HVI length analyzer determines length parameters by photoelectrically scanning a test beard that is selected by a specimen loader and prepared by a comber/brusher attachment

The fibers in the test beard are assumed to be uniform in cross-section, but this is a false assumption because the cross section of each individual fiber in the beard varies significantly from tip to tip. The HVI fiber-length data are converted into the percentage of the total number of fibers present at each length value and into other length parameters, such as mean length, upper-half mean length, and length uniformity . This test method for determining cotton fiber length is considered acceptable for testing commercial shipments when the testing services use the same reference standard cotton samples.

All fiber-length methods discussed above require a minimum of 5 g of ginned fibers and were developed for rapid classing of relatively large, bulk fiber samples. For analyses of small fiber samples , fiber property measurements with an electron-optical particle-sizer, the Zellweger Uster AFIS-A2 have been found to be acceptably sensitive, rapid, and reproducible. The AFIS-A2 Length and Diameter module generates values for mean fiber length by weight and mean fiber length by number, fiber length histograms, and values for upper quartile length, and for short-fiber contents by weight and by number (the percentages of fibers shorter than 12.7 mm). The AFIS-A2 Length and Diameter module also quantifies mean fiber diameter by number .

Although short-fiber content is not currently included in official USDA-AMS classing office reports, short-fiber content is increasingly recognized as a fiber property comparable in importance to fiber fineness, strength, and length . The importance of short-fiber content in determining fiber-processing success, yarn properties, and fabric performance has led the post-harvest sector of the U.S. cotton industry to assign top priority to minimizing short-fiber content, whatever the causes .

The perceived importance of short-fiber content to processors has led to increased demands for development and approval of a standard short-fiber content measurement that would be added to classing office HVI systems . This accepted classing office-measurement would allow inclusion of short-fiber content in the cotton valuation system. Documentation of post-ginning short-fiber content at the bale level is expected to reduce the cost of textile processing and to increase the value of the raw fiber . However, modulation of short-fiber content before harvest cannot be accomplished until the causes of increased short-fiber content are better understood.

Fiber length is primarily a genetic trait, but short-fiber content is dependent upon genotype, growing conditions, and harvesting, ginning, and processing methods. Further, little is known about the levels or sources of pre-harvest short-fiber content .

It is essential that geneticists and physiologists understand the underlying concepts and the practical limitations of the methods for measuring fiber length and short-fiber content so that the strong genetic component in fiber length can be separated from environmental components introduced by excessive temperatures and water or nutrient deficiencies. Genetic improvement of fiber length is fruitless if the responses of the new genotypes to the growth environment prevent full realization of the enhanced genetic potential or if the fibers produced by the new genotypes break more easily during harvesting or processing. The reported effects of several environmental factors on fiber length and short-fiber content, which are assumed to be primarily genotype-dependent, are discussed in the subsections that follow.

FIBER LENGTH AND TEMPERATURE:

Maximum cotton fiber lengths were reached when night temperatures were around 19 to 20 °C, depending on the genotype . Early-stage fiber elongation was highly temperature dependent; late fiber elongation was temperature independent . Fiber length (upper-half mean length) was negatively correlated with the difference between maximum and minimum temperature.

Modifications of fiber length by growth temperatures also have been observed in planting-date studies in which the later planting dates were associated with small increases in 2.5 and 50% span lengths . If the growing season is long enough and other inhibitory factors do not interfere with fiber development, early-season delays in fiber initiation and elongation may be counteracted by an extension of the elongation period .

Variations in fiber length and the elongation period also were associated with relative heat-unit accumulations. Regression analyses showed that genotypes that produced longer fibers were more responsive to heat-unit accumulation levels than were genotypes that produced shorter fibers . However, the earliness of the genotype was also a factor in the relationship between fiber length (and short-fiber content by weight) and accumulated heat units .

As temperature increased, the number of small motes per boll also increased. Fertilization efficiency, which was negatively correlated with small-mote frequency, also decreased. Although fiber length did not change significantly with increasing temperature, the percentage of short-fibers was lower when temperatures were higher. The apparent improvement in fiber length uniformity may be related to increased assimilate availability to the fibers because there were fewer seeds per boll.

FIBER LENGTH AND WATER:

Cotton water relationships and irrigation traditionally have been studied with respect to yield . Fiber length was not affected unless the water deficit was great enough to lower the yield to 700 kg ha-1. Fiber elongation was inhibited when the midday water potential was -2.5 to -2.8 mPa. Occurrence of moisture deficits during the early flowering period did not alter fiber length. However, when drought occurred later in the flowering period, fiber length was decreased .

Severe water deficits during the fiber elongation stage reduce fiber length , apparently due simply to the direct mechanical and physiological processes of cell expansion. However, water availability and the duration and timing of flowering and boll set can result in complex physiological interactions between water deficits and fiber properties including length.

FIBRE LENGTH AND LIGHT:

Changes in the growth environment also alter canopy structure and the photon flux environment within the canopy. For example, loss of leaves and bolls from unfavorable weather (wind, hail), disease, or herbivory and compensatory regrowth can greatly affect both fiber yield and quality . The amount of light within the crop canopy is an important determinant of photosynthetic activity and, therefore, of the source-to-sink relationships that allocate photoassimilate within the canopy . Eaton and Ergle (1954) observed that reduced-light treatments increased fiber length. Shading during the first 7 d after floral anthesis resulted in a 2% increase in the 2.5% span length .

Shading (or prolonged periods of cloudy weather) and seasonal shifts in day length also modulate temperature, which modifies fiber properties, including length.

Commercial cotton genotypes are considered to be day-length neutral with respect to both flowering and fruiting . However, incorporation of day-length data in upland and pima fiber-quality models, based on accumulated heat units, increased the coefficients of determination for the length predictors from 30 to 54% for the upland model and from 44 to 57% for the pima model .

It was found that the light wavelengths reflected from red and green mulches increased fiber length, even though plants grown under those mulches received less reflected photosynthetic flux than did plants grown with white mulches. The longest fiber was harvested from plants that received the highest far red/red ratios.

FIBER LENGTH AND MINERAL NUTRITION:

Studies of the mineral nutrition of cotton and the related soil chemistry usually have emphasized increased yield and fruiting efficiency . More recently, the effects of nutrient stress on boll shedding have been examined . Also, several mineral-nutrition studies have been extended to include fiber quality .

Reports of fiber property trends following nutrient additions are often contradictory due to the interactive effects of genotype, climate, and soil conditions. Potassium added at the rate of 112 kg K ha-1yr-1 did not affect the 2.5% span length , when genotype was a significant factor in determining both 2.5 and 50% span lengths . Genotype was not a significant factor in Acala fiber length, but an additional 480 kg K ha-1yr-1 increased the mean fiber length . K ha-1yr-1 increased the length uniformity ratio and increased 50%, but not 2.5% span length. Genotype and the interaction, genotype-by-environment, determined the 2.5% span length.

As mentioned above, fiber length is assumed to be genotype-dependent, but growth-environment fluctuations - both those resulting from seasonal and annual variability in weather conditions and those induced by cultural practices and inputs - modulate the range and mean of the fiber length population at the test sample, bale, and crop levels.

Quantitation of fiber length is relatively straightforward and reproducible, and fiber length (along with micronaire) is one of the most likely fiber properties to be included when cotton production research is extended beyond yield determinations. Other fiber properties are less readily quantified, and the resulting data are not so easily understood or analyzed statistically. This is particularly true of fiber-breaking strength, which has become a crucial fiber property due to changes in spinning techniques.

FIBER STRENGTH:

The inherent breaking strength of individual cotton fibers is considered to be the most important factor in determining the strength of the yarn spun from those fibers . Recent developments in high-speed yarn spinning technology, specifically open-end rotor spinning systems, have shifted the fiber-quality requirements of the textile industry toward higher-strength fibers that can compensate for the decrease in yarn strength associated with open-end rotor spinning techniques.

Compared with conventional ring spinning, open-end rotor-spun yarn production capacity is five times greater and, consequently, more economical. Rotor-spun yarn is more even than the ring-spun, but is 15 to 20% weaker than ring-spun yarn of the same thickness. Thus, mills using open-end rotor and friction spinning have given improved fiber strength highest priority. Length and length uniformity, followed by fiber strength and fineness, remain the most important fiber properties in determining ring-spun yarn strength.

Historically, two instruments have been used to measure fiber tensile strength, the Pressley apparatus and the Stelometer . In both of these flat-bundle methods, a bundle of fibers is combed parallel and secured between two clamps. A force to try to separate the clamps is applied and gradually increased until the fiber bundle breaks. Fiber tensile strength is calculated from the ratio of the breaking load to bundle mass. Due to the natural lack of homogeneity within a population of cotton fibers, bundle fiber selection, bundle construction and, therefore, bundle mass measurements, are subject to considerable experimental error .

Fiber strength, that is, the force required to break a fiber, varies along the length of the fiber, as does fiber fineness measured as perimeter, diameter, or cross section Further, the inherent variability within and among cotton fibers ensures that two fiber bundles of the same weight will not contain the same number of fibers. Also, the within-sample variability guarantees that the clamps of the strength testing apparatus will not grasp the various fibers in the bundle at precisely equivalent positions along the lengths. Thus, a normalizing length-weight factor is included in bundle strength calculations.

In the textile literature, fiber strength is reported as breaking tenacity or grams of breaking load per tex, where tex is the fiber linear density in grams per kilometer . Both Pressley and stelometer breaking tenacities are reported as 1/8 in. gauge tests, the 1/8 in. (or 3.2 mm) referring to the distance between the two Pressley clamps. Flat-bundle measurements of fiber strength are considered satisfactory for acceptance testing and for research studies of the influence of genotype, environment, and processing on fiber (bundle) strength and elongation.

The relationships between fiber strength and elongation and processing success also have been examined using flat-bundle strength testing methods . However cotton fiber testing today requires that procedures be rapid, reproducible, automated, and without significant operator bias. Consequently, the HVI systems used for length measurements in USDA-AMS classing offices are also used to measure the breaking strength of the same fiber bundles (beards) formed during length measurement.

Originally, HVI strength tests were calibrated against the 1/8-in. gauge Pressley measurement, but the bundle-strengths of reference cottons are now established by Stelometer tests that also provide bundle elongation-percent data. Fiber bundle elongation is measured directly from the displacement of the jaws during the bundle-breaking process, and the fiber bundle strength and elongation data usually are reported together (ASTM, 1994, D 4604-86). The HVI bundle-strength measurements are reported in grams-force tex-1 and can range from 30 and above (very strong) to 20 or below (very weak). In agronomic papers, fiber strengths are normally reported as kN m kg-1, where one Newton equals 9.81 kg-force .

The HVI bundle-strength and elongation-percent testing methods are satisfactory for acceptance testing and research studies when 3.0 to 3.3 g of blended fibers are available and the relative humidity of the testing room is adequately controlled. A 1% increase in relative humidity and the accompanying increase in fiber moisture content will increase the strength value by 0.2 to 0.3 g tex-1, depending on the fiber genotype and maturity.

Further, classing-office HVI measurements of fiber strength do not adequately describe the variations of fiber strength along the length of the individual fibers or within the test bundle. Thus, predictions of yarn strength based on HVI bundle-strength data can be inadequate and misleading . The problem of fiber-strength variability is being addressed by improved HVI calibration methods and by computer simulations of bundle-break tests in which the simulations are based on large single-fiber strength databases of more than 20 000 single fiber long-elongation curves obtained with MANTIS .

Fiber Strength, Environment, and Genotype:

Reports of stelometer measurements of fiber bundle strength are relatively rare in the refereed agronomic literature. Consequently, the interactions of environment and genotype in determining fiber strength are not as well documented as the corresponding interactions that modulate fiber length. Growth environment, and genotype response to that environment, play a part in determining fiber strength and strength variability .

Early studies showed fiber strength to be significantly and positively correlated with maximum or mean growth temperature, maximum minus minimum growth temperature, and potential insolation . Increased strength was correlated with a decrease in precipitation. Minimum temperature did not affect fiber strength. All environmental variables were interrelated, and a close general association between fiber strength and environment was interpreted as indicating that fiber strength is more responsive to the growth environment than are fiber length and fineness. Other investigators reported that fiber strength was correlated with genotype only.

Square removal did not affect either fiber elongation or fiber strength . Shading, leaf-pruning, and partial fruit removal decreased fiber strength . Selective square removal had no effect on fiber strength in bolls at the first, second, or third position on a fruiting branch . Fiber strength was slightly greater in bolls from the first 4 to 6 wk of flowering, compared with fibers from bolls produced by flowers opening during the last 2 wk of the flowering period .

In that study, fiber strength was positively correlated with heat unit accumulation during boll development, but genotype, competition among bolls, assimilatory capacity, and variations in light environment also helped determine fiber strength. Early defoliation, at 20% open bolls, increased fiber strength and length, but the yield loss due to earlier defoliation offset any potential improvement in fiber quality .

FIBER MATURITY:

Of the fiber properties reported by USDA-AMS classing offices for use by the textile industry, fiber maturity is probably the least well-defined and most misunderstood. The term, fiber maturity, used in cotton marketing and processing is not an estimate of the time elapsed between floral anthesis and fiber harvest . However, such chronological maturity can be a useful concept in studies that follow fiber development and maturation with time . On the physiological and the physical bases, fiber maturity is generally accepted to be the degree (amount) of fiber cell-wall thickening relative to the diameter or fineness of the fiber .

Classically, a mature fiber is a fiber in which two times the cell wall thickness equals or exceeds the diameter of the fiber cell lumen, the space enclosed by the fiber cell walls . However, this simple definition of fiber maturity is complicated by the fact that the cross section of a cotton fiber is never a perfect circle; the fiber diameter is primarily a genetic characteristic.

Further, both the fiber diameter and the cell-wall thickness vary significantly along the length of the fiber. Thus, attempting to differentiate, on the basis of wall thickness, between naturally thin-walled or genetically fine fibers and truly immature fibers with thin walls greatly complicates maturity comparisons among and within genotypes.

Within a single fiber sample examined by image analysis, cell-wall thickness ranged from 3.4 to 4.9 µm when lumen diameters ranged from 2.4 to 5.2 µm . Based on the cited definition of a mature fiber having a cell-wall thickness two times the lumen diameter, 90% of the 40 fibers in that sample were mature, assuming that here had been no fiber-selection bias in the measurements.

Unfortunately, none of the available methods for quantifying cell-wall thickness is sufficiently rapid and reproducible to be used by agronomists, the classing offices, or fiber processors. Fiber diameter can be quantified, but diameter data are of limited use in determining fiber maturity without estimates of the relationship between lumen width and wall thickness. Instead, processors have attempted to relate fiber fineness to processing outcome.

Estimating Fiber Fineness:

Fiber fineness has long been recognized as an important factor in yarn strength and uniformity, properties that depend largely on the average number of fibers in the yarn cross section. Spinning larger numbers of finer fibers together results in stronger, more uniform yarns than if they had been made up of fewer, thicker fibers . However, direct determinations of biological fineness in terms of fiber or lumen diameter and cell-wall thickness are precluded by the high costs in both time and labor, the noncircular cross sections of dry cotton fibers, and the high degree of variation in fiber fineness.

Advances in image analysis have improved determinations of fiber biological fineness and maturity , but fiber image analyses remain too slow and limited with respect to sample size for inclusion in the HVI-based cotton-classing process.

Originally, the textile industry adopted gravimetric fiber fineness or linear density as an indicator of the fiber-spinning properties that depend on fiber fineness and maturity combined . This gravimetric fineness testing method was discontinued in 1989, but the textile linear density unit of tex persists. Tex is measured as grams per kilometer of fiber or yarn, and fiber fineness is usually expressed as millitex or micrograms per meter . Earlier, direct measurements of fiber fineness (either biological or gravimetric) subsequently were replaced by indirect fineness measurements based on the resistance of a bundle of fibers to airflow.

The first indirect test method approved by ASTM for measurement of fiber maturity, lineardensity, and maturity index was the causticaire method. In that test, the resistance of a plug of cotton to airflow was measured before and after a cell-wall swelling treatment with an 18% (4.5 M) solution of NaOH (ASTM, 1991, D 2480-82). The ratio between the rate of airflow through an untreated and then treated fiber plug was taken as indication of the degree of fiber wall development. The airflow reading for the treated sample was squared and corrected for maturity to serve as an indirect estimate of linear density. Causticaire method results were found to be highly variable among laboratories, and the method never was recommended for acceptance testing before it was discontinued in 1992.

The arealometer was the first dual-compression airflow instrument for estimating both fiber fineness and fiber maturity from airflow rates through untreated raw cotton (ASTM, 1976, D 1449-58; Lord and Heap, 1988). The arealometer provides an indirect measurement of the specific surface area of loose cotton fibers, that is, the external area of fibers per unit volume (approximately 200-mg samples in four to five replicates). Empirical formulae were developed for calculating the approximate maturity ratio and the average perimeter, wall thickness, and weight per inch from the specific surface area data. The precision and accuracy of arealometer determinations were sensitive to variations in sample preparation, to repeated sample handling, and to previous mechanical treatment of the fibers, e.g., conditions during harvesting, blending, and opening. The arealometer was never approved for acceptance testing, and the ASTM method was withdrawn in 1977 without replacement.

The variations in biological fineness and relative maturity of cotton fibers that were described earlier cause the porous plugs used in air-compression measurements to respond differently to compression and, consequently, to airflow . The IIC-Shirley Fineness/Maturity Tester (Shirley FMT), a dual-compression instrument, was developed to compensate for this plug-variation effect (ASTM, 1994, D 3818-92). The Shirley FMT is considered suitable for research, but is not used for acceptance testing due to low precision and accuracy. Instead, micronaire has become the standard estimate of both fineness and maturity in the USDA-AMS classing offices.

Fiber Maturity and Environment:

Whatever the direct or indirect method used for estimating fiber maturity, the fiber property being as sayed remains the thickness of the cell wall. The primary cell wall and cuticle (together »0.1 µm thick) make up about 2.4% of the total wall thickness (»4.1 µm of the cotton fiber thickness at harvest) . The rest of the fiber cell wall (»98%) is the cellulosic secondary wall, which thickens significantly as polymerized photosynthate is deposited during fiber maturation. Therefore, any environmental factor that affects photosynthetic C fixation and cellulose synthesis will also modulate cotton fiber wall thickening and, consequently, fiber physiological maturation

Fiber Maturity and Temperature and Planting Date:

The dilution, on a weight basis, of the chemically complex primary cell wall by secondary-wall cellulose has been followed with X-ray fluorescence spectroscopy. This technique determines the decrease, with time, in the relative weight ratio of the Ca associated with the pectin-rich primary wall . Growth-environment differences between the two years of the studies cited significantly altered maturation rates, which were quantified as rate of Ca weight-dilution, of both upland and pima genotypes. The rates of secondary wall deposition in both upland and pima genotypes were closely correlated with growth temperature; that is, heat-unit accumulation .

Micronaire (micronAFIS) also was found to increase linearly with time for upland and pima genotypes . The rates of micronaire increase were correlated with heat-unit accumulations . Rates of increase in fiber cross-sectional area were less linear than the corresponding micronaire-increase rates, and rates of upland and pima fiber cell-wall thickening were linear and without significant genotypic effect .

Environmental modulation of fiber maturity (micronaire) by temperature was most often identified in planting- and flowering-date studies . The effects of planting date on micronaire, Shirley FMT fiber maturity ratio, and fiber fineness (in millitex) were highly significant in a South African study (Greef and Human, 1983). Although genotypic differences were detected among the three years of that study, delayed planting generally resulted in lower micronaire. The effect on fiber maturity of late planting was repeated in the Shirley FMT maturity ratio and fiber fineness data.

Planting date significantly modified degree of thickening, immature fiber fraction, cross-sectional area, and micronaire (micronAFIS) of four upland genotypes that also were grown in South Carolina . In general, micronaire decreased with later planting, but early planting also reduced micronaire of Deltapine 5490, a long-season genotype, in a year when temperatures were suboptimal during the early part of the season.

Harvest dates in this study also were staggered so that the length of the growing season was held constant within each year. Therefore, season-length should not have been an important factor in the relationships found between planting date and fiber maturity.

Fiber Maturity and Source-Sink Manipulation:

Variations in fiber maturity were linked with source-sink modulations related to flowering date , and seed position within the bolls . However, manipulation of source-sink relationships by early-season square (floral bud) removal had no consistently significant effect on upland cotton micronaire in one study . However, selective square removal at the first, second, and third fruiting sites along the branches increased micronaire, compared with controls from which no squares had been removed beyond natural square shedding . The increases in micronaire after selective square removals were associated with increased fiber wall thickness, but not with increased strength of elongation percent. Early-season square removal did not affect fiber perimeter or wall thickness (measured by arealometer) . Partial defruiting increased micronaire and had no consistent effect on upland fiber perimeter in bolls from August flowers.

Fiber Maturity and Water:

Generous water availability can delay fiber maturation (cellulose deposition) by stimulating competition for assimilates between early-season bolls and vegetative growth . Adequate water also can increase the maturity of fibers from mid-season flowers by supporting photosynthetic C fixation. In a year with insufficient rainfall, initiating irrigation when the first-set bolls were 20-d old increased micronaire, but irrigation initiation at first bloom had no effect on fiber maturity. Irrigation and water-conservation effects on fiber fineness (millitex) were inconsistent between years, but both added water and mulching tended to increase fiber fineness. Aberrations in cell-wall synthesis that were correlated with drought stress have been detected and characterized by glycoconjugate analysis .

An adequate water supply during the growing season allowed maturation of more bolls at upper and outer fruiting positions, but the mote counts tended to be higher in those extra bolls and the fibers within those bolls tended to be less mature . Rainfall and the associated reduction in insolation levels during the blooming period resulted in reduced fiber maturity . Irrigation method also modified micronaire levels and distributions among fruiting sites.

Early-season drought resulted in fibers of greater maturity and higher micronaire in bolls at branch positions 1 and 2 on the lower branches of rainfed plants. However, reduced insolation and heavy rain reduced micronaire and increased immature fiber fractions in bolls from flowers that opened during the prolonged rain incident. Soil water deficit as well as excess may reduce micronaire if the water stress is severe or prolonged .

Fiber Maturity and Genetic Improvement:

Micronaire or maturity data now appear in most cotton improvement reports . In a five-parent half-diallel mating design, environment had no effect on HVI micronaire . However, a significant genotypic effect was found to be associated with differences between parents and the F1 generation and with differences among the F1 generation. The micronaire means for the parents were not significantly different, although HVI micronaire means were significantly different for the F1 generation as a group. The HVI was judged to be insufficiently sensitive for detection of the small difference in fiber maturity resulting from the crosses. In another study, F2 hybrids had finer fibers (lower micronaire) than did the parents, but the improvements were deemed too small to be of commercial value. Unlike the effects of environment on the genetic components of other fiber properties, variance in micronaire due to the genotype-by-environment interaction can reach levels expected for genetic variance in length and strength . Significant interactions were found between genetic additive variance and environmental variability for micronaire, strength, and span length in a study of 64 F2 hybrids. The strong environmental components in micronaire and fiber maturity limit the usefulness of these fiber properties in studies of genotypic differences in response to growth environment. Based on micronaire, fiber maturity, cell-wall thickness, fiber perimeter, or fiber fineness data, row spacing had either no or minimal effect on okra-leaf or normal-leaf genotypes . Early planting reduced micronaire, wall-thickness, and fiber fineness of the okra-leaf genotype in one year of that study. In another study of leaf pubescence, nectaried vs. no nectaries, and leaf shape, interactions with environment were significant but of much smaller magnitude than the interactions among traits. Micronaire means for Bt transgenic lines were higher than the micronaire means of Coker 312 and MD51ne when those genotypes were grown in Arizona . In two years out of three, micronaire means of all genotypes in this study, including the controls, exceeded 4.9; in other words, were penalty grade. This apparent undesirable environmental effect on micronaire may have been caused by a change in fiber testing methods in the one year of the three for which micronaire readings were below the upper penalty limit. Genotypic differences in bulk micronaire may either be emphasized or minimized, depending on the measurement method used .

GRADE: In U.S. cotton classing, nonmandatory grade standards were first established in 1909, but compulsory upland grade standards were not set until 1915 . Official pima standards were first set in 1918. Grade is a composite assessment of three factors - color, leaf, and preparation . Color and trash (leaf and stem residues) can be quantified instrumentally, but traditional, manual cotton grade classification is still provided by USDA-AMS in addition to the instrumental HVI trash and color values. Thus, cotton grade reports are still made in terms of traditional color and leaf grades; for example, light spotted, tinged, strict low middling.

Preparation: There is no approved instrumental measure of preparation - the degree of roughness/smoothness of the ginned lint. Methods of harvesting, handling, and ginning the cotton fibers produce differences in roughness that are apparent during manual inspection; but no clear correlations have been found between degree of preparation and spinning success. The frequency of tangled knots or mats of fiber (neps) may be higher in high-prep lint, and both the growth and processing environments can modulate nep frequency. However, abnormal preparation occurs in less than 0.5% of the U.S. crop during harvesting and ginning.

Trash or Leaf Grade: Even under ideal field conditions, cotton lint becomes contaminated with leaf residues and other trash. Although most foreign matter is removed by cleaning processes during ginning, total trash extraction is impractical and can lower the quality of ginned fiber. In HVI cotton classing, a video scanner measures trash in raw cotton, and the trash data are reported in terms of the total trash area and trash particle counts (ASTM, D 4604-86, D 4605-86). Trash content data may be used for acceptance testing. In 1993, classer's grade was split into color grade and leaf grade . Other factors being equal, cotton fibers mixed with the smallest amount of foreign matter have the highest value. Therefore, recent research efforts have been directed toward the development of a computer vision system that measures detailed trash and color attributes of raw cotton. The term leaf includes dried, broken plant foliage, bark, and stems particles and can be divided into two general categories: large-leaf and pin or pepper trash. Pepper trash significantly lowers the value of the cotton to the manufacturer, and is more difficult and expensive to remove than the larger pieces of trash.Other trash found in ginned cotton can include stems, burs, bark, whole seeds, seed fragments, motes (underdeveloped seeds), grass, sand, oil, and dust. The growth environment obviously affects the amount of wind-borne contaminants trapped among the fibers. Environmental factors that affect pollination and seed development determine the frequency of undersized seeds and motes. Reductions in the frequencies of motes and small-leaf trash also have been correlated with semi-smooth and super-okra leaf traits. Environment (crop year), harvest system, genotype, and second order interactions between those factors all had significant effects on leaf grade. Delayed harvest resulted in lower-grade fiber. The presence of trash particles also may affect negatively the color grade.

Fiber Color: Raw fiber stock color measurements are used in controlling the color of manufactured gray, bleached, or dyed yarns and fabrics. Of the three components of cotton grade, fiber color is most directly linked to growth environment. Color measurements also are correlated with overall fiber quality so that bright (reflective, high Rd), creamy-white fibers are more mature and of higher quality than the dull, gray or yellowish fibers associated with field weathering and generally lower fiber quality . Although upland cotton fibers are naturally white to creamy-white, pre-harvest exposure to weathering and microbial action can cause fibers to darken and to lose brightness. Premature termination of fiber maturation by applications of growth regulators, frost, or drought characteristically increases the saturation of the yellow (+b) fiber-color component. Other conditions, including insect damage and foreign matter contamination, also modify fiber color.The ultimate acceptance test for fiber color, as well as for finished yarns and fabrics, is the human eye. Therefore, instrumental color measurements must be correlated closely with visual judgment. In the HVI classing system, color is quantified as the degrees of reflectance (Rd) and yellowness (+b), two of the three tri-stimulus color scales of the Nickerson-Hunter colorimeter. Fiber maturity has been associated with dye-uptake variability in finished yarn and fabric, but the color grades of raw fibers seldom have been linked to environmental factors or agronomic practices during production.**Other Environmental Effects on Cotton Fiber Quality:** Although not yet included in the USDA-AMS cotton fiber classing system, cotton stickiness is becoming an increasingly important problem . Two major causes of cotton stickiness are insect honeydew from whiteflies and aphids and abnormally high levels of natural plant sugars, which are often related to premature crop termination by frost or drought. Insect honeydew contamination is randomly deposited on the lint in heavy droplets and has a devastating production-halting effect on fiber processing. The cost of clearing and cleaning processing equipment halted by sticky cotton is so high that buyers have included honeydew free clauses in purchase contracts and have refused cotton from regions known to have insect-control problems. Rapid methods for instrumental detection of honeydew are under development for use in classing offices and mills.

FIBER QUALITY OR FIBER YIELD?

Like all agricultural commodities, the value of cotton lint responds to fluctuations in the supply-and-demand forces of the marketplace. In addition, pressure toward specific improvements in cotton fiber quality - for example, the higher fiber strength needed for today's high-speed spinning - has been intensified as a result of technological advances in textile production and imposition of increasingly stringent quality standards for finished cotton products.

Changes in fiber-quality requirements and increases in economic competition on the domestic and international levels have resulted in fiber quality becoming a value determinant equal to fiber yield. Indeed, it is the quality, not the quantity, of fibers ginned from the cotton seeds that decides the end use and economic value of a cotton crop and, consequently, determines the profit returned to both the producers and processors. Wide differences in cotton fiber quality and shifts in demand for particular fiber properties, based on end-use processing requirements, have resulted in the creation of a price schedule, specific to each crop year, which includes premiums and discounts for grade, staple length, micronaire, and strength. This price schedule is made possible by the development of rapid, quantitative methods for measuring those fiber properties considered most important for successful textile production. With the wide availability of fiber-quality data from HVI, predictive models for ginning, bale-mix selection and fiber-processing success could be developed for textile mills.

Price-analysis systems based on HVI fiber-quality data also became feasible. Quantization, predictive modeling, and statistical analyses of what had been subjective and qualitative fiber properties are now both practical and common in textile processing and marketing. Field-production and breeding researchers, for various reasons, have failed to take full advantage of the fiber-quality quantization methods developed for the textile industry. Most field and genetic improvement studies still focus on yield improvement while devoting little attention to fiber quality beyond obtaining bulk fiber length, strength, and micronaire averages for each treatment . Indeed, cotton crop simulation and mapping models of the effects of growth environment on cotton have been limited almost entirely to yield prediction and cultural-input management.

Plant physiological studies and textile-processing models suggest that bulk fiber-property averages at the bale, module, or crop level do not describe fiber quality with sufficient precision for use in a vertical integration of cotton production and processing. More importantly, bulk fiber-property means do not adequately and quantitatively describe the variation in the fiber populations or plant metabolic responses to environmental factors during the growing season. Such pooled or averaged descriptors cannot accurately predict how the highly variable fiber populations might perform during processing.Meaningful descriptors of the effects of environment on cotton fiber quality await high-resolution examinations of the variabilities, induced and natural, in fiber-quality averages. Only then can the genetic and environmental sources of fiber-quality variability be quantified, predicted, and modulated to produce the high-quality cotton lint demanded by today's textile industry and, ultimately, the consumer. Increased understanding of the physiological responses to the environment that interactively determine cotton fiber quality is essential. Only with such knowledge can real progress be made toward producing high yields of cotton fibers that are white as snow, as strong as steel, as fine as silk, and as uniform as genotypic responses to the environment will allow.