TEXTILE topics

VOLUME 2008-1
Winter

International Textile Center | Texas Tech University Lubbock, Texas USA

New ITC Laboratory Goes Online

An additional 5,500 square feet of controlled ambient condition (21 °C ±1 ° and 65% RH ± 2%) have been added to the International Textile Center laboratory complex; all high-volume, heat producing instruments for testing fibers and yarns have been relocated to the new space; and the expanded laboratory is fully functional. The large, contiguous space enables more rigorous controls over sample conditioning and more efficient flows of materials to be tested.

The previously existing space for the Materials Evaluation Laboratory is being reconfigured to house the instrumentation necessary for evaluating the structural/molecular properties of fibers and polymers. This laboratory is already operating on a limited basis and will be aggressively developed during coming months.

Sharing current research information and trends in the fiber and textile industries.

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Texas International Cotton School Announces Dates of Next Session

The Texas International Cotton School (TICS) will be offered during the period of August 11-22, 2008. Domestic and international participants in the cotton and textile sectors are cordially invited to register and attend. Visit http://www.texasintlcottonschool.com for full details or to register online.

More than 400 students from 54 different countries have participated in the intensive two-week course. Conducted at the International Textile Center and hosted by the Lubbock Cotton Exchange, the TICS curriculum provides hands-on instruciton in cotton breeding, production, harvesting, ginning, classing, testing, processing, transporting, marketing, exporting, logistics and more. It offers students an integrated, vertical understanding of the U.S. Cotton Industry and its interactions with the ever-changing global cotton/textile complex.

International Textile Center Partners with CASNR Department

In 1998, the International Textile Center (ITC) joined the College of Agricultural Sciences and Natural Resources (CASNR) at Texas Tech University. Another structural milestone was reached, when, effective December 1, 2007, the ITC merged with the Department of Plant and Soil Science (PSS) within CASNR. This merger occurred following approval of the Texas Board of Higher Education and began 1 December, 2007.

The objectives for the merger are to 1) increase the performance and external support of both units, 2) enhance existing synergy between the units to increase total research funding, expand the research mission, and foster efficient use of physical plants; 3) increase enrollment in graduate programs within the department, and 4) develop Plant and Soil Science as the pre-eminent department in the U.S. for research and teaching on cotton genetics/genomics, production, and processing.

The International Textile Center will retain its name and location on East Loop 289, and its operations will continue to be led by the Managing Director, Dr. Dean Ethridge.

FIBER LENGTH DISTRIBUTION IN COTTON PROCESSING: DOMINANT FEATURES AND INTERACTION EFFECTS

Mourad Krifa

The following is a reprint, by permission, of an article in the Textile Research Journal (TRJ 76(5): 426-435). In addition, support for this research is provided by the Food and Fibers Research Program of the Texas Department of Agriculture

Among all measured characteristics of cotton fiber, length has always been considered to be the most crucial. The end-use of the fiber and the processes adopted for its transformation are largely determined by its length properties.

Notwithstanding the early statements to the effect that adequately describing the length of a fiber sample is only possible by considering the entire distribution [1, 2], the cotton industry has focused primarily on measuring the length of the longest fibers in a cotton sample. This long-established practice derived from the early methods of manual classing based on the concept of staple length and was carried over by the evolution and modernization of length measurement instruments (span lengths, upper half mean length, upper quartile length…). For decades, these parameters have accommodated the measurement needs of the cotton industry. However, in recent years the problem of short fibers has come to the forefront of concerns for the global cotton industry. Indeed, with the evolution toward high-speed production technologies, the mechanical treatments undergone by the fiber became more and more aggressive. This along with more stringent requirements imposed on raw cotton quality, has increasingly shifted interest towards the short fibers.

The adverse effects of short fibers have become the subject of a unanimous consensus among all sectors of the cotton industry, which made the objective of minimizing short fibers a top priority in cotton research. In the research reported to date, a variety of length measurement methods were used to quantify short fibers. Various parameters were defined for this purpose. Tallant et al. [2, 3] defined the short fiber content as the percentage of fibers 9.53 mm (0.375 inch) and shorter. Lord [1] used the percentage of fibers shorter than half the "effective length" as a definition. Lord also introduced the percentage of fibers shorter than a fixed length as a possible useful definition for some particular purposes. Eventually, all definitions evolved into a single measure arbitrarily defined as the percentage of fibers shorter than 12.7 mm (0.5 inch), and designated as the "short fiber content" or SFC.

Early instruments to measure fiber length distribution were based on the comb sorter, or staple diagram, formed by manually arranging the fibers in ordered length groups. The Sutter–Webb array is one of these methods and is usually used as a reference for length distribution measurement [4], although it is widely acknowledged that its reliability is limited due to its tediousness and dependence on operative skill and experience [5].

High volume instrument (HVI) length measurement provides the "fibrogram", or the second integral of the length frequency histogram [6–8]. It is used to derive three main parameters: the mean length (ML), the upper half mean length (UHML; average length of the 50% longest fibers by weight, used for staple classification), and the uniformity index (ratio of ML to UHML expressed in %). Note that among all the parameters made available by the existing range of instruments and methods, the uniformity index (or the uniformity ratio) represents the only commonly used shape parameter of the length distribution [8].

Attempts have been made to estimate short fibers from the HVI using different techniques. The simplest consist of establishing regression equations between HVI length parameters and the SFC [9–11]. Other approaches are based on deriving the entire length frequency histogram from the fibrogram [9, 12–14].

Another major instrument used by the cotton industry to measure fiber length distribution is the Advanced Fiber Information System (AFIS®) from Uster Technologies [15–18]. It measures properties of single fibers individualized by an aeromechanical device and conveyed by airflow to a set of optical sensors, where they are counted and characterized. Among other fiber properties (fineness, maturity, neps and trash particles), the AFIS® provides a variety of length parameters: mean length by number (Ln), and by weight (Lw), upper quartile length by weight (UQLw), length CV% by weight and by number, short fiber content by weight (SFCw%) and by number (SFCn%) and length upper percentiles by number (Ln2.5% and Ln5%). It must be emphasized that the length distribution by number constitutes the source of all these parameters. The weight-biased distribution (and parameters) is estimated from the latter based on the assumption of a uniform fineness across all length categories. (Strictly speaking, the distribution "by weight" is in fact a length-biased distribution.)

The use of the AFIS for length distribution measurement has become more and more prevalent as a result of the increased concern regarding short fibers. The prominence of the short fiber issue has eventually refocused the interest on the notion of length distribution, as recommended by Lord [1] and others over many decades, and attempts have been repeatedly made to provide length data that is representative of the entire distribution. The AFIS has the functionality necessary to generate a complete histogram of the length distribution of cotton samples; however, this is seldom if ever done in commercial applications. Effective utilization of length histogram data requires an understanding of the unique shape of the cotton fiber length distribution and the difficulties inherent to its parameterization. This paper examines some of the issues related to the shape of cotton fiber length distribution, its main features and its determining factors.

Material and Methods

A range of 67 commercial cotton bales grown in three US production areas over two crop seasons (2002, 2003) were selected. Each bale was sampled at 10 layers throughout, with fiber measurements being done on each layer. The main HVI fiber properties of the selected bales are summarized in Table 1 (four replications for Micronaire, four for color, and 10 for length and strength).

In addition to HVI analysis, all samples were tested on AFIS® (three replications of 3000 fibers each) and length histogram data were retrieved, along with the usual parameters. The latter are also summarized in Table 1. Finally, on a subset of the bales, additional length distribution data were obtained from fiber samples collected after an aggressive opening action performed by a fiber individualizer of the type used in open-end rotor spinning.

We examined all this data to evaluate the characteristic shape of cotton fiber length distribution and its main features. The relationships

Table I: Main fiber properties of the selected bales (HVI and AFIS measurements on bale samples).

Fiber properties	*Min.*	*Max.*	*Average*
HVI			
Micronaire	2.3	5.1	4.2
Upper Half Mean Length (UHML, mm)	24.9	30.8	27.6
Length uniformity (%)	79.0	84.1	81.6
Strength (g/tex)	22.3	33.9	29.3
Elongation (%)	3.7	9.5	6.7
AFIS			
Mean length by number (Ln, mm)	15.1	22.0	19.1
Short Fiber Content by number (SFCn, %)	18.2	41.4	26.8
Mean length by weight (Lw, mm)	19.8	26.8	23.8
Short Fiber Content by weight (SFCw, %)	5.5	15.4	9.5
Upper Quartile Length by weight (UQLw, mm)	25.0	32.1	28.8
Maturity Ratio (MR)	0.76	0.95	0.89
Fineness (mtex)	151	190	172

Table 1 - *Main fiber properties of the selected bales (HVI and AFIS measurements on bale samples).*

and interactions between these features (distributional shape) and the structural properties of cotton fibers (maturity, fineness, strength…) were then explored. Finally, issues relating to the alteration of the length distribution pattern when the fiber was subjected to mechanical processing were considered.

As previously mentioned, given the nature of the AFIS test (single fibers), the numerical length distribution (by number) constitutes the source from which all length parameters are derived (both by number and by weight). The following discussion is based on numerical length distribution data. Issues relating to the length-biased distribution (by weight) will be treated at a later stage of the research.

Results and Discussion

Length Distribution Pattern

The examination of AFIS results obtained on the 67 cotton bales revealed some typical features of the length distribution patterns. Figure 1 depicts the results for two groups of four cottons each, exemplifying the varied length distribution patterns encountered (with similar staple lengths within groups: 24.9 to 25.4 mm and 27.9 to 28.4 mm, respectively).

Despite the different patterns, all cottons presented a local peak in the range of very short fibers (3.2 mm or 0.125 inch). The precise origin of this fiber fragment accumulation is, at this point, unclear. However, it is likely to be related to fiber breakage occurring during the mechanical processing of the fiber, or during the testing procedure itself. Indeed, it is necessary to bear in mind the aggressive opening action exerted by the AFIS in order to individualize the fibers.

A similar peak was noticed by Schneider et al. [19] using a measurement method based on image analysis, and was attributed to fiber breakage during ginning. Schenek et al. [17] used a manual method for single fiber length measurement [20] and noticed a close agreement with the AFIS®

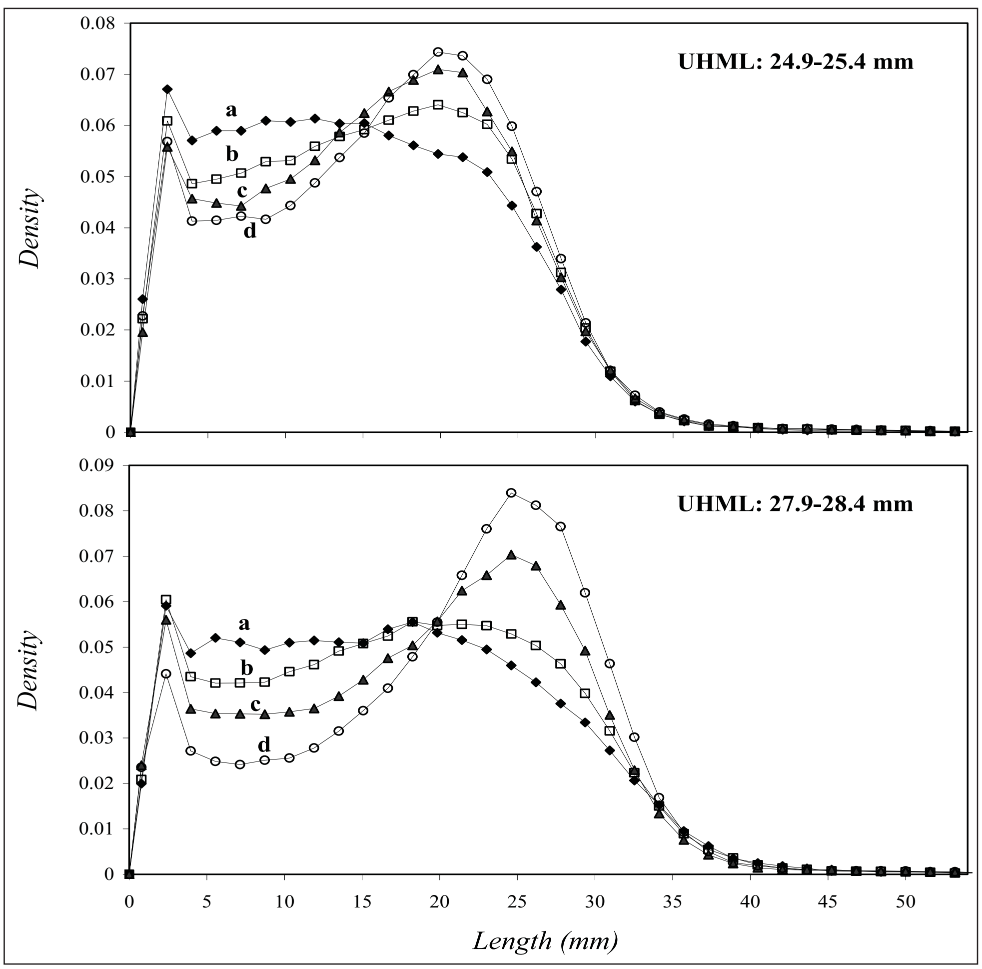

Figure 1 *Length distribution pattern Group 1:* UHML = *24.9–25.4 mm (staple 31–32); Group 2:* UHML = *27.9–28.4 mm (staple 35–36).*

distribution in the range of short fibers. This suggests that the accumulation of fiber fragments predominantly occurred in the course of fiber mechanical handling (ginning, lint cleaning), rather than during the AFIS opening.

In addition to the fiber fragment peak (3.2 mm), four of the distributions (patterns (c) and (d) in each of the graphs of Figure 1) show a second distinct mode towards the longer fibers with a dip between the two peaks. The length distribution labeled (a), on the other hand, presents an almost flat plateau with the only discernible peak located at 3.2 mm.

Examination of the main fiber properties of the bales that were tested revealed that the distribution patterns shown above were associated with different levels of fiber maturity and strength. To illustrate this dependence, fiber maturity was used as a selection criterion and constituted two sets of cottons, with differing maturity levels. Fiber bundle strength levels measured by HVI were, of course, different between the two sets, given the inherent relationships among the complex maturity-fineness and strength.

The first set of samples was characterized by a maturity ratio of 0.79 and less (immature, weak fibers), whereas the second set was made up of cottons having a maturity ratio exceeding 0.9 (mature, strong fibers). The length distributions of the two sets of samples are shown in Figure 2.

The similarities in the distribution patterns within each set (i.e., each maturity and strength level) are obvious. The immature weak cottons show length distributions similar to the pattern designated (a), whereas the mature strong cottons exhibit a distribution comparable to the pattern labeled (d) (compare with Figure 1).

These observations strongly suggest a significant influence of maturity and strength on the shape of fiber length distribution. The most apparent distribution feature affected by these properties is the existence or non-existence of

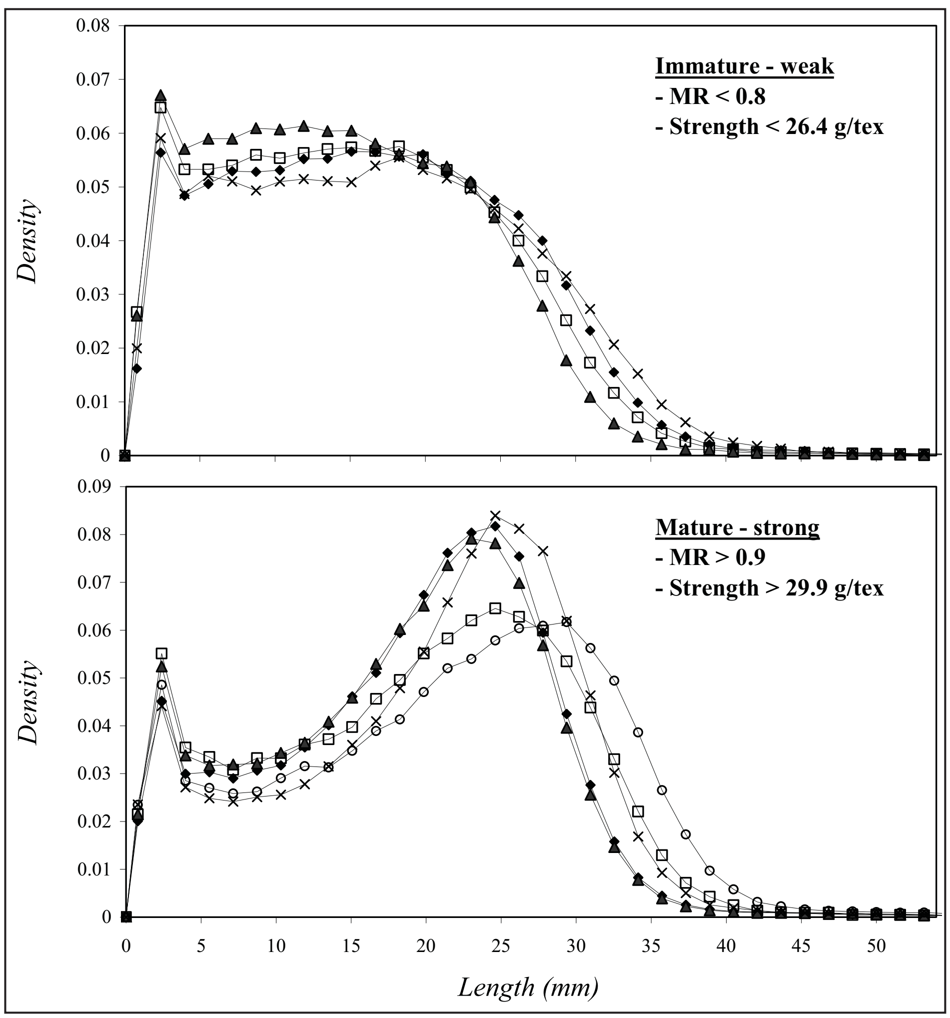

Figure 2 *Observed length distribution for immature-weak and mature-strong fibers.*

two distinct modes. Based on the results illustrated in Figure 2, immature and weak cottons exhibit a unimodal distribution whereas mature and strong ones tend to show a bimodal length distribution.

As stated above, these observations are based on visual inspection of the length distribution shapes of two sets of selected cottons with significantly different maturity andstrength values (extreme cases). In order to generalize the conclusions and allow inclusion of a wider range of cotton samples (including intermediate cases, i.e., with average maturity and strength), a parametric description of length distribution is required.

Modality of the Length Distribution

As a first approach the focus was placed on describing of the modality of the distributions, since this feature represented the most visually striking difference between length distributions of immature-weak cottons (unimodal pattern) and mature-strong ones (bimodal pattern). To explore these characteristics objectively, a formal statistical tool was sought to quantitatively measure the strength of bimodality and determine its statistical significance (or, in more general terms, measure multi-modality; that is, to quantify evidence against unimodality).

There are several methods reported in the literature that help test the modality and determine the number of modesin an empirical distribution [21–25]. Hartigan's DIP test for unimodality [23, 24] was used for two main reasons. First, the test is based on calculation of the DIP statistic, which quantitatively measures departure from unimodality. This would provide a quantitative criterion that can be used to discriminate between the distributional shapes within the range of cottons. Second, the DIP test is distribution-free; i.e., it does not require *a priori* assumptions on the nature of the distribution being observed.

Hartigan and Hartigan [23] define the DIP statistic as "the maximum difference, overall sample points, between the empirical distribution function, and the unimodal distribution that minimizes that maximum difference" (i.e., the maximum difference between the empirical CDF and the unimodal CDF closest to it, with CDF: cumulative distribution function). Derivation of the DIP statistic is based on the fundamental definition of a unimodal distribution function, which stipulates that a distribution function $F(x)$ is unimodal with mode m if $F(x)$ is convex in the interval $(-\infty, m]$ and concave in $[m, \infty)$ [23, 26]; $F(x)$ being the cumulative distribution function or CDF. The unimodal CDF closest to the empirical distribution F, given the mode m_0 is, by virtue of the definition above, the greatest convex minorant of F on $(-\infty, m_0]$ and the least concave majorant on $[m_0, \infty)$ [23, 24, 27]. (The greatest convex minorant of F on $(-\infty, m_0]$ is defined as "the convex function G not exceeding F on $(-\infty, m_0]$ that minimizes $\sup_{x \le m_0} |F(x)-G(x)|$." The least concave majorant is defined analogously) [23, 27].

Further description of the principles underlying the computation of the DIP statistic can be found in the open literature, [23, 24, 27]. The original FORTRAN routine written by Hartigan to compute the DIP statistic can be found in reference [24]; an updated version of the FORTRAN routine can be found in [28]. A translation of the latter into Matlab was used to do the computations in the present study.

Figure 3 shows two length distribution histograms, as generated by AFIS®, with an illustration of the DIP statistic concept. Note that, as specified above, the DIP statistic is computed based on CDF fits and cannot be quantified from PDF representations. However, the latter is used in Figure 3 due to its visual impact, which seemed more appropriate for illustrating the modality concept in the present case.

The upper graph in Figure 3 (case a) represents the empirical length histogram of an immature-weak cotton, along with the plot of the unimodal PDF closest to it, derived based on Hartigan's procedure (broken line). In this first case (immature-weak cotton), the DIP statistic is estimated at 0.0027 and the unimodal fit appears rather close to the empirical histogram.

The bottom graph in Figure 3 (case b) shows an analogous representation of the length distribution of a mature, strong cotton. The discrepancy between the unimodal fit and the empirical data appears greater than in the previous case. The DIP statistic adequately reflects this

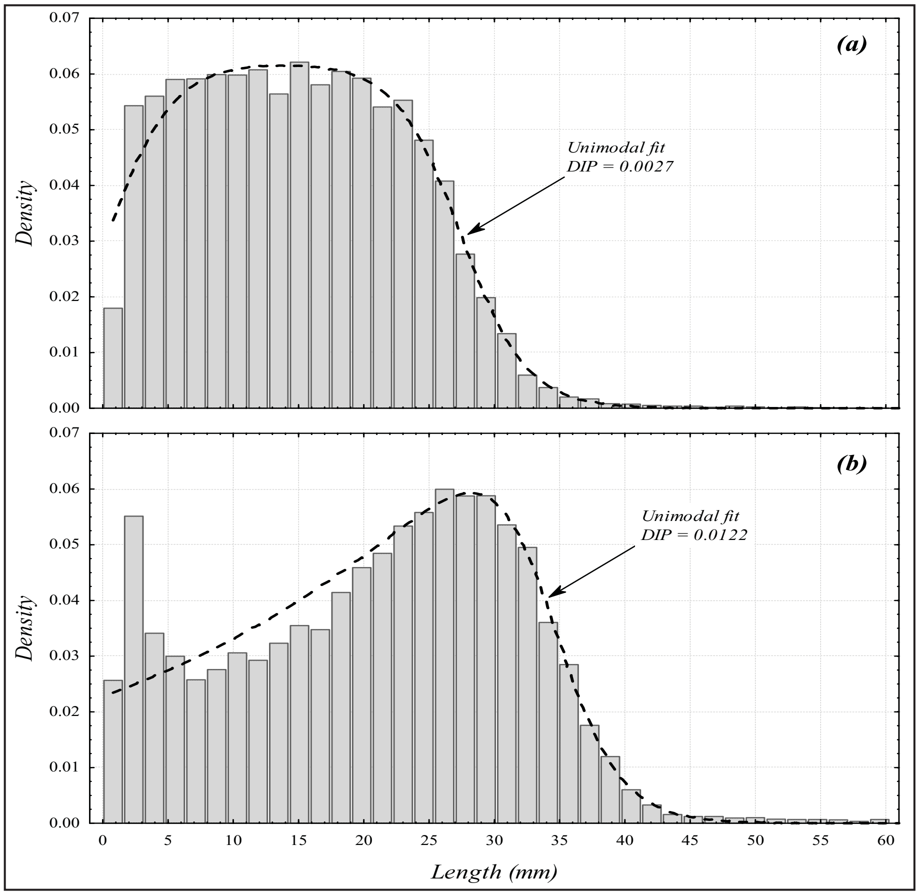

Figure 3 *Illustration of the modality test.*
(a) Immature-weak cotton;
(b) Mature-strong cotton.

discrepancy and its value is 4.5-times higher than for the immature-weak cotton (0.0122 compared to 0.0027).

The concepts illustrated above were applied to all the length distribution data collected from AFIS® analysis. Using the raw fiber data (ten layers per bale), the DIP statistic was estimated for each individual layer in order to examine the variation of the distribution modality within bales of cotton (between layers), in addition to the variation among different cottons. The results are summarized in the box plots of Figure 4 (67 juxtaposed plots, one box plot represents one cotton bale).

The box plots of Figure 4 show DIP statistic values that appear rather dispersed within some of the tested bales (with a varying degree of scatter from one bale to another, and some apparent outliers; the outliers are defined as those observed values higher than the upper quartile plus 1.5 × IQR and lower than the lower quartile –1.5 × IQR, with IQR being the inter-quartile range [29]). The number of observations made on each bale (10 layers) was not sufficient for a thorough analysis of the within-bale distribution of the DIP statistic and of the incidence of outliers. On the other hand, the results were ample to show a highly significant between-bale variability of the distribution modality measure, as evidenced by both the parametric one-way ANOVA and the non-parametric Kruskal–Wallis test, which yielded low probability values associated with the between-groups (bale-to-bale) comparison ($p < 0.001$, see Figure 4).

As previously stated, observations made

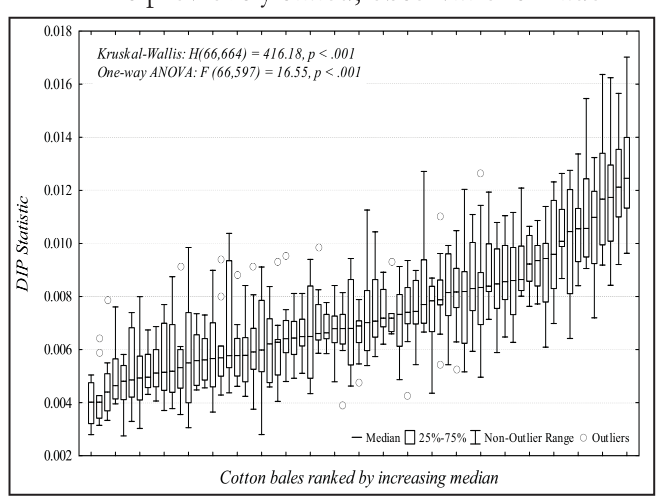

Figure 4 *Box plots of the DIP statistic computed from individual layer data for the 67 cotton bales.*

on selected cottons (Figures 2 and 3) suggested a close relationship between the length distribution modality (or, more generally, shape) and some fundamental structural properties of the cotton (maturity–fineness, strength). Using the quantitative measure of the distribution modality (DIP statistic), it is now possible to examine these relationships over the entire set of cottons that were tested.

Table 2 contains simple correlation coefficients obtained between the calculated length distribution modality parameter and the fiber properties mentioned above (based on the average values of the 10 layers). With the exception of fiber fineness, the correlation coefficients were highly significant for all parameters (namely micronaire, fiber strength, and maturity ratio). Strength, micronaire and maturity ratio exhibited positive correlation coefficients, indicating that the stronger and more mature cottons had length distributions that departed more appreciably from unimodality. The strongest correlation was with fiber strength.

Scatter plots relating the length distribution modality to fiber strength and maturity ratio are shown in Figures 5 and 6, respectively. As suggested by the correlation coefficients of Table 2, the data points are more dispersed when considering the relationship involving maturity (Figure 6). Nevertheless, both plots exhibit a marked curvilinear trend and display a larger scatter towards high strength and high maturity levels. This pattern suggests that low strength and maturity levels invariably result in a fiber length distribution that is virtually unimodal (low DIP values, with little variation from one cotton sample to another). High strength and maturity levels, on the other hand, show globally higher DIP statistic values that varied over a considerably wider range.

Table II: Correlation between fiber properties and length distribution modality (DIP statistic)

Fiber Property	*Correlation coefficient*	*Prob.*
HVI		
Micronaire	0.48	<.001
Strength (g/tex)	0.76	<.001
AFIS		
Maturity Ratio (MR)	0.52	<.001
Fineness (mtex)	0.15	0.237

Table 2 *Correlation between fiber properties and length distribution modality (DIP statistic).*

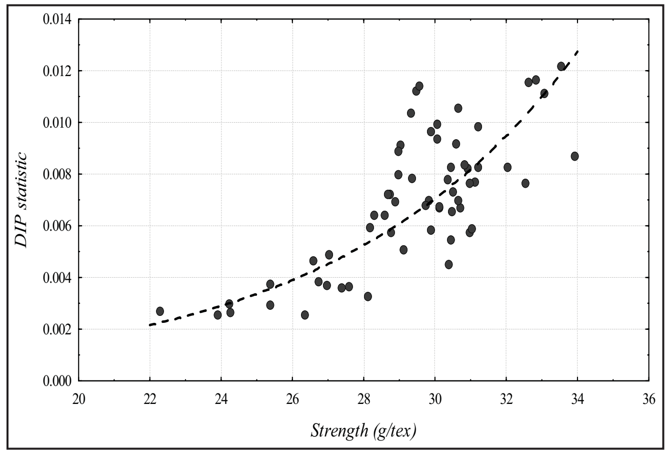

Figure 5 R*elationship between length distribution modality (DIP) and fiber strength.*

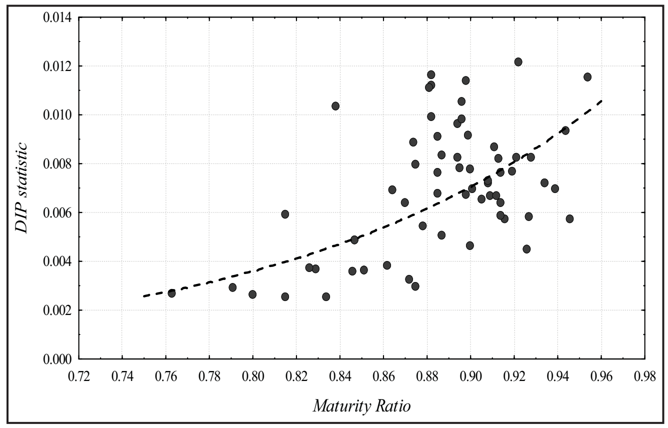

Figure 6 R*elationship between length distribution modality (DIP) and maturity ratio.*

The increased variability that accompanied higher maturity and strength levels might be due to interaction effects of other fiber properties (e.g., fineness), as well as to differences in mechanical or other damage done to the fibers. Based on the patterns of Figures 5 and 6, it appears conceivable that immature-weak cottons will show a unimodal length distribution (low DIP value) almost independently from the aggressiveness of the upstream processes to which they were subjected (the fibers will break even under relatively gentle conditions). The length distribution modality of mature-strong cottons, on the other hand, will show a greater dependence on the aggressiveness of the processes (and possibly other fiber properties), which explains the greater scatter observed on Figures 5 and 6 (along with the higher DIP values) for high strength and maturity levels.

To further explore this issue, the following paragraph is dedicated to examining the changes in fiber length distribution pattern, particularly its modality, when the cottons were subjected to aggressive opening operations.

Length Distribution Alteration during Processing

A unimodal distribution (with a low DIP value) signals extensive breakage of cotton fibers. This pattern is characteristic of an immature-weak cotton, but could also be observed for a mature-strong cotton that has an aggressive processing history (i.e., was subjected to excessive damage). Figures 7 and 8 illustrate the change of the length distribution patterns of two selected cottons that had been processed through an aggressive opening action (see fiber individualizer in "Methods" section).

cotton (Figure 7) shifted toward shorter lengths and took a shape that resembled, rather strikingly, those observed in Figure 1 (pattern (a)) and Figure 2 (immature-weak cottons).

As for the immature-weak cotton (Figure 8), its distribution appeared to be squeezed towards the left end of the length axis; i.e., it became dominated by short fibers. Obviously there was no change in the modality in this second case, the raw fiber length distribution being already unimodal.

These results highlight the close relationship between the length distribution modality and the mechanical damage incurred by the fiber. Particularly, a unimodal distribution observed at the raw-fiber stage is a clear indication of excessive fiber damage due either to fiber immaturity and weakness or to poor conditions in upstream processes (excessive aggressiveness).

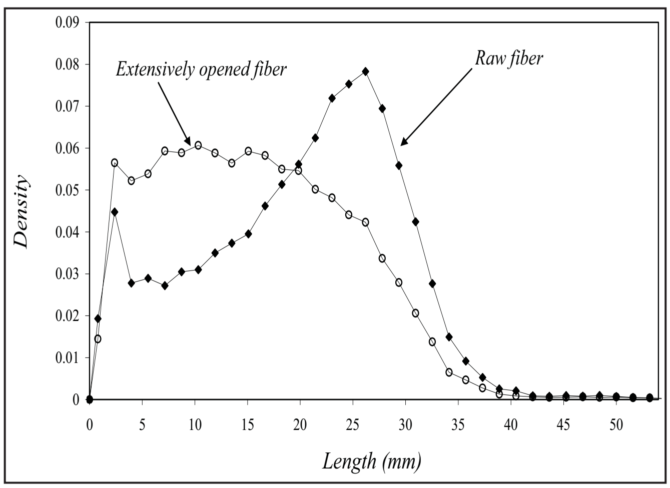

Figure 7 *Length distribution pattern alteration after aggressive mechanical opening – Case 1: mature-strong cotton (with a bimodal initial length distribution).*

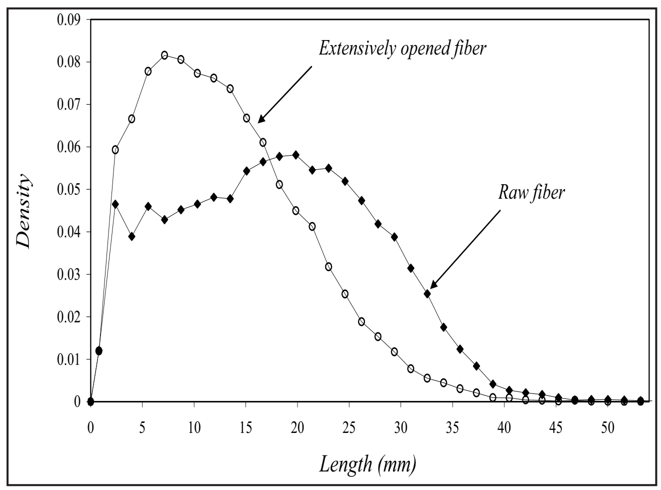

Figure 8 *Length distribution pattern alteration after aggressive mechanical opening – Case 2: immature-weak cotton (with a unimodal initial length distribution).*

One can rightly infer from the bimodal shape of the initial distribution (raw fiber) that the cotton depicted in Figure 7 was a relatively mature and strong one. The data shown in Figure 8, on the other hand, corresponds to a cotton with lower strength and maturity levels, and its length distribution (raw fiber) shows no evidence of bimodality.

After undergoing the aggressive mechanical action of the fiber opener-individualizer, neither of the two cottons showed evidence of bimodality. The initially bimodal distribution of the mature-strong

Summary Discussion

The present results showed that the shape of fiber length distribution was dependent both on the processing history of the cotton and on those fiber properties that determine the behavior of the cotton during these processing phases (i.e., its propensity to break). The modality feature (existence of one single, or two distinct modes in the distribution) seems to be representative of this dependence. Cottons with low propensity to break have bimodal length distributions that evolve toward unimodality under further mechanical damage. Cottons with a high propensity to break (immature-weak) have length distribution patterns with no evidence of bimodality even in the early stages of the cotton process. At these stages, a measure of the distribution modality could provide valuable clues that are relevant to the processing history of any given cotton, as well as to the length alteration behavior to be expected in further processing. Such a measure could represent a diagnostic tool for optimizing the handling and utilization of the cotton fibers.

Several aspects related to this research remain to be investigated. For instance, processes preceding the compressed bale, ginning in particular, are currently being investigated in order to determine where in the cotton chain the bimodal structure of the distribution first appears. Clues available to date seem to point to the gin stand as the genesis of this bimodal structure. However, conclusive research with a special focus on the distribution modality and its evolution at the gin is yet to be completed. Objectives pursued in the author's current research also include identifying the main factors (varietal, environmental, process-related…) that affect the cottons' propensity to break. Furthermore, other features of the fiber length distribution are still being explored, with the primary objective of fully parameterizing its pattern and describing its interactions with the processing performance of cotton. Results related to these aspects will be described in future publications.

Conclusions

Using a broad range of 67 cotton bales, the fiber length distribution pattern was examined and the interactions involving its features were explored. The results revealed important interactions relating the shape of fiber length distribution to strength and maturity properties and to mechanical processing of the cottons. The shape of the length distribution depends on both: (1) the resistance to breakage (or propensity to break) inherent to the fiber; and (2) the aggressiveness of the mechanical processes to which the cotton is subjected. One prominent distributional feature revealed in the analysis is the modality of the distribution (or departure from unimodality). Evidence of bimodality observed in length distributions of bale samples (raw cotton) appeared to correlate with high resistance to breakage (higher strength and more mature fibers). Subjecting the raw fiber to mechanical stresses (opening, cleaning…) appeared, through a process of breakage, to gradually dissipate the bimodal structure of the distribution, which shifted towards shorter lengths. Eventually, after sufficient mechanical damage has been administered to the fibers, the bimodal character of the distribution evolved into a unimodal one.

Some samples showed no evidence of bimodality in the bale. These correspond to cottons with low maturity and strength values; i.e., having a higher propensity to break. The unimodal structure can also result from excessive mechanical treatment of the fiber during harvesting, ginning, and lint cleaning.

One relevant question raised by these results - "where in the cotton chain does the bimodal structure of the length distribution first appear?" Data collected up to now, along with clues available from the literature, indicate that it may start at the gin stand. However, further analysis of the type presented herein is to be performed on fiber samples collected in the upstream processes (preceding the spinning mill) in order to answer this question. Another issue to be considered is that despite the relevant information revealed by consideration of the distribution modality, other features of the cotton fiber length distribution.

Acknowledgement

The Texas Food and Fibers Commission supported this research.

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