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Creation of a Set of Reference Material for Cotton Fiber Maturity Measurements

Abstract It was the goal of the authors to create a set of reference cottons for maturity measurements. To achieve this they selected 104 cotton bales representing the two principal cultivated species. The vast majority of the bales originated in the USA, but some foreign-grown cotton bales were also selected (Egypt, Uzbekistan, Pakistan, Cameroon, Syria, Benin, and Australia). A representative sample of approximately 30 kg (70 pounds) was taken from each bale. Each sample was homogenized according to the protocol used by the International Cotton Calibration Standard Committee (ICCS) to produce reference cottons. Eight sub-samples per bale were taken and a minimum of 500 cross-sections per sub-sample were analyzed. A broad range of average values of fiber perimeter and fiber maturity for the 104 bales were obtained. Evaluation of the mathematical and statistical relationships pertinent to maturity and fineness revealed that four critical criteria for adequate calibration standards were met. Therefore, this population of bales constitutes a good base for the calibration of the indirect measurement instruments for maturity and fineness.

Key words cotton fiber, standard cotton, cross-section, maturity, theta, fineness, perimeter

The effect of maturity on the dye uptake is well-known (that is the basis of the Goldthwait test, [1]). Similarly, the authors know that fine and mature fibers make it possible to spin a finer yarn. Furthermore, maturity and fineness of cotton fibers are also essential qualitative characteristics if one wants to better understand the facility of rupture of fibers when they are subjected to stress. It is intuitively obvious to hypothesize that immature fibers (having a thin, poorly developed secondary wall) will be fragile. Thus, they are likely to break during multiple mechanical stresses involved in transforming the fibers from the field to the yarn. These generate short fibers and neps (entanglement of fibers). An increase in the short fiber content will result in yarn defects and decreased productivity.

In spite of the importance of maturity and fineness for the textile industry, there is no direct or indirect measure-

**Eric F. Hequet¹, Bobby Wyatt, and
Noureddine Abidi**

*International Textile Center – Texas Tech University,
Lubbock, TX, 79403, USA*

Devron P. Thibodeaux

SRRC – USDA – ARS, New Orleans, LA, 70124, USA

ment method that is both fast and reliable. The lack of standards of reference for maturity has made it impossible to calibrate the existing instruments (air flow instruments with double compression, Advanced Fiber Information System – Maturity module). Even the dominant qualitative criterion for fineness/maturity, the micronaire, cannot be further refined without a current reference method.

The definitional reference for the measurement of maturity and fiber perimeter is the microscopic analysis of cotton fiber cross-sections. Lord [2] established on 100 cottons the relationship between micronaire and the product maturity $\times$ fineness. It should be noted that maturity was determined

¹ Corresponding author; e-mail: eric.hequet@ttu.edu

Figure 1 Sampling procedure.

on swollen fibers (sodium hydroxide treatment) and the gravimetric fineness by the “cut and weigh” method; i.e., forming a parallel fiber bundle, cutting a 1-cm section in the median portion, weighing the cut fibers, and counting the number of fibers [3]. In Lord’s method, five bundles were selected for each sample: one from the longest fibers of an array, one from the 1.5 cm group and three equally spaced in between [4]. Both of these methods introduce bias into the measurements. Lord’s method for maturity swells the fibers with sodium hydroxide and the degree of swelling is not independent of the quantity of cellulose. The “cut and weigh” method is not independent of fiber length because only fibers longer than 1.5 cm are evaluated. Prakash and Ilengar [5] reported that Lord’s method of measuring the gravimetric fineness gives results 8 to 10% higher than weighing the whole fibers.

Given that the reference cottons created by Lord are no longer available, it becomes necessary to create a new set of reference cottons. In doing this, it is critical that the intra-standard variability be as low as possible and that the quantity of reference materials be large enough to meet the needs of the international scientific community for at least 10 years.

Experimental

Bale Selection and Sampling

The authors selected 104 cotton bales representing the two principal cultivated species (*Gossypium hirsutum* and *Gossypium barbadense*, [6]). The vast majority of the bales originated in the USA, but some foreign-grown cotton bales

were also selected (Egypt, Uzbekistan, Pakistan, Cameroon, Syria, Benin, and Australia). The bales were opened and ten samples per bale were taken. Each sample was tested using a HVI Uster 900A. A total of 40 micronaire tests and 100 length and tenacity tests were performed for each bale.

A representative sample of approximately 30 kg (70 pounds) was taken from each bale (Figure 1). Each sample was homogenized according to the protocol used by the International Cotton Calibration Standard Committee (ICCS) [7] to produce reference cottons. From the card web produced, 20 samples were taken. Samples 1 to 5 were re-sampled (8 pinches per sample). This new sample was delicately mixed manually then two fibrograph combs were formed. The authors chose to sample with the fibrosampler because this method, unlike Lord’s method, is not length biased [8]. This procedure was repeated for samples 6–10, 11–15 and 16–20. A sample was then taken from each of the eight combs produced (Figure 2). For each comb, a minimum of 500 cross-sections were analyzed. When the CV% of the averages between combs was higher than 2%, eight other combs were produced and 500 additional cross-sections (per

Figure 2 Fiber sample produced with the Fibrosampler.

comb) were analyzed. The original CV% was confirmed in almost every case.

Realization of the Cross-sections

The method used to embed the sample is a modified version of the methacrylate embedding method developed by Boylston of the USDA-SRRC New Orleans [9]. The methacrylate polymer holds the cotton fibers until they can be glued to a slide for observation and then the methacrylate polymer is dissolved in methyl ethyl ketone (MEK). Tests were done to control that cotton fibers do not swell or shrink when treated with MEK. Ribbon width was measured under the microscope with and without MEK treatment. The average ribbon width was 20.0 μm without MEK compared with 19.5 μm with MEK (difference not statistically significant).

The methacrylate polymer is a mix of 60 parts methyl methacrylate, 40 parts butyl methacrylate and 2 parts benzoyl peroxide. This solution is prepared and partially polymerized (heated to 75°C for about 40 minutes) into what is called the MBM Stock. A second solution of "pre-catalyst" is prepared, consisting of 18 parts of methyl methacrylate and 2 parts of benzoyl peroxide. Both of these solutions are refrigerated.

To embed the cotton fibers, 5 ml of the MBM Stock and 1 ml of the pre-catalyst are mixed, then the fibers are suspended from a fine wire and dipped into the solution (Figure 3). The wire is then drawn up a Teflon tube (1.6 mm internal diameter and 0.8 mm wall thickness) with the lower end of the tube below the surface of the solution. The tube is stoppered with a toothpick at the bottom and filled with solution from the top, to eliminate air, then stoppered with another toothpick at the top. Finally, the sample-filled tube is placed in the UV chamber (Ultraviolet Crosslinker, from UVP Inc., modified to hold 14 lights of 302 nm) for 20 to 30 minutes.

After polymerization, the Teflon tube is removed. The sample (approximately 25.4 mm length) is inserted in a second Teflon tube (3.2 mm internal diameter and 0.8 mm wall

thickness). The lower end of the tube is closed with a cork stopper (0000) and filled with solution. The top is then closed with the same type of stopper. Then, the sample is placed in a UV chamber to polymerize the solution (which takes another 20 to 30 minutes). The tube is then removed. The sample is placed in a third Teflon tube (7.9 mm internal diameter and 0.8 mm wall thickness). The lower end of the tube is closed with a cork stopper (0) and filled with solution. The top is closed with the same type of stopper. This tube is placed in a UV chamber to polymerize (another 20 to 30 minutes), after which the Teflon tube is removed. This process produces a sample with a diameter that fits well into the sample holder of the microtome (MT 990: Boeckeler Instruments Inc., Tucson, AZ, USA). Before mounting the sample on the microtome, approximately 6 to 12 mm are cut with a razor blade. The glass knife of the microtome is then used to obtain a perfectly plane surface. Finally the diamond knife is used to make the cross-sections (1 μm thick) which are to be observed with the microscope.

Glass slides for microscopic observation are coated with albumin glue, then dried prior to sectioning the samples. The glue is made of equal quantities of glycerin and egg-white intimately mixed. The slides are coated with a thin layer of this preparation. Two water drops are deposited on a slide and one section is placed on each water drop. The slide is placed on a glass rod support in a Petri dish above chloroform for 3 seconds. This gives the thin polymer time to smooth and allows the cross-sections to scatter slightly. This allows a better separation of the fibers, thereby facilitating the microscopic observation. The slide is then placed on a hotplate (very briefly and at low temperature) to eliminate water and to fix the cross-sections in the glue. The slide is then allowed to condition in standard atmosphere, and then washed with the MEK for approximately 4 hours, to eliminate the methacrylate polymer and leave the cross-sections glued in place on the slide.

After the slides are prepared the images are viewed with the microscope (40 $\times$ objective) and captured in the computer using a Hitachi 3CCD Camera Model HVC-20 with a Coreco Oculus TCX Frame Grabber. Finally the images are analyzed (Figure 4) by the FIAS software developed by Bugao Xu of UT Austin [10].

Calculation of Maturity Ratio, Fineness, and Standard Fineness from Cotton Fiber Cross-sections

Figure 5 shows the schematic of a cotton fiber cross-section, from which we can deduce the following equations:

$$\begin{aligned} A_w &= \pi R_2^2 - \pi R_1^2 \\ &= \pi(R_2^2 - R_1^2) \end{aligned} \quad (1)$$

Figure 3 Fiber sample being inserted in the Teflon tubing.

(a)

(b)

Figure 4 Cross-section analysis with the Fias software: (a) original image (b) processed image.

where A_w is the cell-wall area (cross-sectional area minus lumen area) in μm^2 , R_1 represents the inside radius, and R_2 represents the outside radius.

One can also calculate the degree of secondary wall thickening, θ (no unit). Theta (θ) is defined as the ratio of the area of the cell wall to the area of a circle having the same perimeter as the fiber section [3].

$$\theta = \frac{\pi(R_2^2 - R_1^2)}{\pi R_2^2} = \frac{A_w}{\pi R_2^2} = \frac{A_w}{\pi \left(\frac{P_2}{2\pi}\right)^2} = \frac{4\pi A_w}{P_2^2} \quad (2)$$

Figure 5 Schematic of a cotton fiber cross section.

where θ is the degree of secondary wall thickening (no unit) and P_2 is the outside perimeter of the fiber in microns.

Furthermore, fiber fineness (H) is given by:

$$H = \rho A_w \quad (3)$$

where H is the fiber fineness expressed in mtex and ρ is the cell-wall density in g/cm^3 ($\rho = 1.52 \text{ g/cm}^3$).

The standard fineness (H_s) is given by the following equation:

$$H_s = \frac{H}{M} = 0.577 \frac{H}{\theta} = \frac{0.577 A_w \rho}{\theta} = \frac{0.577 A_w \rho P_2^2}{4\pi A_w} \quad (4)$$

$$H_s = \frac{0.577 \rho P_2^2}{4\pi} \quad (4)$$

where H_s is the standard fineness expressed in mtex and M is the maturity ratio ($M = \theta/0.577$).

The outside perimeter of the fiber can be expressed as a function of the fiber standard fineness as follows:

$$P_2 = \sqrt{\frac{4\pi}{0.577 \times 1.52}} H_s = 3.7853 \sqrt{H_s} \quad (5)$$

Therefore, if we consider that the density of the cell wall is constant, the measurement of the wall cross-sectional area and the external diameter provides us with all the information we need. In general the scientific community is interested in three parameters derived from these

two measurements: the maturity ratio M ($M = \frac{\theta}{0.577} = \frac{4\pi A_w}{0.577 P_2^2}$), the fineness H ($H = \rho A_w$) and the standard fineness H_s ($H_s = \frac{0.577 \rho P_2^2}{4\pi}$).

Results and Discussion

As stated earlier, for each bale a total of 40 micronaire tests and 100 length and tenacity tests were performed.

This allowed the authors to conclude that the intra-bale variability was acceptable and that we had a broad range of average values of micronaire, length, and tenacity (Table 1).

As stated in the introduction, in spite of the importance of maturity and fineness for the textile industry, a fast and

Table 1 HVI fiber properties of the 104 bales: basic statistics.

	Micronaire	UHML (inch)	UI (%)	Tenacity (cN/tex)	Elongation (%)
Average	4.2	1.08	81.9	29.4	5.4
Minimum	2.6	0.96	78.6	21.6	3.6
Maximum	5.7	1.31	84.5	41.3	8.3
Intra-bale CV%					
Average	0.7	0.9	0.6	1.9	3.5
Minimum	0.0	0.4	0.2	0.8	1.4
Maximum	2.2	2.2	1.1	3.1	7.7

Figure 6 Two-dimensional distributions (perimeter and theta) of cottons having similar micronaires: (a) bale 3142, (b) bale 3016, (c) bale 3056, (d) bale 3004.

reliable measurement method is still not available. The industry is routinely using only the micronaire as an indication of the complex maturity-fineness. However, the micronaire measurement is somewhat confusing, as shown in Figure 6. Indeed, cottons having identical micronaires may have very different two-dimensional (2-D) distributions of perimeter and theta. These distribution differences will translate into different processing efficiency and yarn quality. The micronaire is therefore a rather bad descriptor of the inherent complexity of the quality attributes we are attempting to describe.

The distributions of both maturity and perimeter need to be described as precisely as possible. Among the parameters that may have an influence on distributions is the sampling procedure. The authors chose to use the fibrosampler technique described above, whereas Lord chose the cut-and-weigh method [2].

The impact of the sampling procedure on maturity and fineness measurements will be illustrated with an example. For the bale 3016 the samples were prepared with the fibrosampler and the cut-and-weigh method, i.e., forming a parallel fiber bundle, cutting a 1-cm section in the median portion, counting the number of fibers, and weighing the cut fibers. This differs slightly from Lord's method in which the fibers were sampled by length group (see above). Figure 7 shows the 2-D histograms of perimeter and theta for the two types of sampling.

It is clear that the cut-and-weigh method offers a tightened distribution when compared with the one obtained with the fibrosampler. Indeed, in this example, the longest fibers tend also to have a slightly larger perimeter and to be more mature. Thus by eliminating short fibers, the cut-and-weigh method over-estimates the perimeter and maturity and under-estimates their variances. This was confirmed on a set of 6 cottons (Table 2). Peeters reviewing the bibliogra-

phy available, concluded that: "Although there are sometimes contradictions in literature, ... within a seed cotton sample, long fibers are finer, stronger and more mature than short fibers" [11]. This is true for seed cotton samples but not always for processed cottons.

Processing, i.e., harvesting, ginning, opening and carding lead to fiber breakage. For a given level of maturity, finer fibers (small diameter) would have a higher propensity to break than coarser fibers. Therefore, with the cut-and-weigh method, excluding fibers shorter than 1 cm has potential to bias the sample as the finer shorter broken fibers are not sampled adequately.

The authors have also confirmed independently the possible influence of a skew in the length distribution on maturity measurements using several ICCS cottons [12]. The fibers were separated by length group (Array method, ASTM D-1440, [13]), and then the fibers of each length group were subjected to cross-sectioning and observed under the microscope. Figure 8 shows the results obtained with the ICCS cotton C37. A relationship length-perimeter, and length-maturity appears clearly. It should be noted that this relationship is not identical for all cottons, as for some of them the maturity varies only a little with the length. Indeed, the conditions of growth of the plant have an influence on the length and maturity distributions. When the conditions are optimal throughout the growth of the plant almost all the fibers can reach their full maturity whereas they cannot if the conditions are below the optimum.

This sampling procedure using the fibrosampler seems to be less biased than the cut-and-weigh method. The results obtained by Lord, which are still a reference today, show at least two biases which could be eliminated or reduced with our method (sampling with the fibrosampler rather than the cut-and-weigh method, no swelling of the fibers with caustic soda). In 1956, Lord studied 100 cottons and established the

Figure 7 Effect of the sampling method on the two-dimensional histograms (perimeter - theta): (a) sampling with the fibrosampler; (b) sampling with the cut-and-weigh method.

Table 2 Sampling methods comparison (6 bales – 16 samples per bale – 500 cross-sections per sample).

	Fibrosampler			Cut-and-weigh		
	Mean	CV% between fibers	CV% between replications	Mean	CV% between fibers	CV% between replications
Bale 2684						
Perimeter (μ)	45.4	16.8	1.8	46.1	14.0	1.7
Area (μ^2)	83.8	34.4	4.1	92.1	27.7	3.2
Theta	0.525	31.5	2.0	0.557	27.0	2.5
Bale 3016						
Perimeter (μ)	53.8	18.4	2.0	55.7	14.3	2.7
Area (μ^2)	107.4	36.6	4.5	122.4	29.2	5.1
Theta	0.480	34.1	2.7	0.507	29.2	2.2
Bale 3107						
Perimeter (μ)	53.6	16.6	1.7	54.7	13.6	2.4
Area (μ^2)	122.0	29.8	3.2	130.5	25.3	5.0
Theta	0.547	27.0	1.6	0.558	24.7	2.1
Bale 3140						
Perimeter (μ)	44.7	17.1	3.3	46.4	14.1	2.6
Area (μ^2)	96.6	34.7	6.2	109.5	29.1	5.6
Theta	0.613	25.5	1.7	0.642	21.5	2.2
Bale 3151						
Perimeter (μ)	50.6	17.0	1.7	52.1	14.4	1.9
Area (μ^2)	101.8	34.8	3.9	110.5	30.3	3.7
Theta	0.512	31.6	1.9	0.522	28.9	2.1
Bale 3169						
Perimeter (μ)	55.2	18.1	1.8	55.8	15.0	2.7
Area (μ^2)	120.1	34.4	5.0	122.4	29.5	5.1
Theta	0.511	32.4	2.5	0.508	30.0	2.0
Averages						
Perimeter (μ)	50.6	17.3	2.1	51.8	14.2	2.3
Area (μ^2)	105.3	34.1	4.5	114.6	28.5	4.6
Theta	0.531	30.3	2.1	0.549	26.9	2.2

following relationship between micronaire and the product *MH*:

$$MH = 3.86Mike^2 + 18.16Mike + 13.0 \quad (R^2 = 0.981). \quad (6)$$

The coefficient of determination obtained is curiously high when it is considered that the micronaire is measured with an air flow apparatus, maturity by microscopic analysis and the fineness by "cut-and-weigh" method. The relationship between micronaire and the product *MH* obtained from

Figure 8 Relationship between (a) length group (array method) and perimeter (perimeter = $-0.006 \text{ length}^2 + 0.422 \text{ length} + 47.3$; $R^2 = 0.625$; $F(2,7) = 5.83$; $p = 0.032$; standard error of estimate = 1.2), and (b) between length group and theta (theta = $-0.000132 \text{ length}^2 + 0.009975 \text{ length} + 0.339$; $R^2 = 0.941$; $F(2,7) = 55.66$; $p = 0.0001$; standard error of estimate = 0.0104).

image analysis of the cotton fiber cross-sections should be different from the relationship using Lord's equation. Therefore, there is a need to revisit this relationship.

From the image analysis results one can calculate the maturity ratio M as follows:

$$M = (N - D)/200 + 0.7 \quad (3) \quad (7)$$

where N is the percentage of normal fibers ($\theta \geq 0.5$) and D is the percentage of dead fibers ($\theta \leq 0.25$).

Alternately, one could calculate M as follows:

$$M = \frac{4\pi A_w}{0.577 P_2^2} = \frac{\theta}{0.577} \quad (8)$$

The two calculations are not equivalent. The assignment of values to theta of 0.5 and 0.25 for the boundaries between normal-immature and immature-dead fibers made by Pierce and Lord [3] was only an approximation. The actual values were determined for only 15 varieties. They had ranges of 0.45 to 0.56 and 0.15 to 0.32, respectively, with means of 0.506 and 0.243 (A. Heap, personal communication). Therefore, it is not justified to calculate M with the Pierce and Lord equation. The second equation based on the circularity of the cotton fiber cross-sections appears to be more adequate.

Then, one can calculate the fineness H as follows:

$$H = \rho \text{ Area} \quad (9)$$

or

$$H = \text{Total Area}/v \quad (10)$$

with ρ = cell wall density = 1.52; v = specific volume of cotton fibers = 0.75 [14].

If this equality were true, the regression between the two fineness calculations should give a slope of 1, an intercept of 0 and a correlation coefficient of 1.0. The experimental data presented in Figure 9 show that the slope is very close to 1 [confidence interval of the slope is (1.014, 1.024)], the intercept is 0 and the coefficient of correlation is 0.97 (coefficient of determination is 0.934). It is therefore reasonable to assume that the use of average values for cell wall density and specific volume is justified.

An examination of the basic equations for micronaire, maturity and fineness must inform us on the type of relationship to expect between the product MH and the micronaire (quadratic or linear). The modeling of an air flow in a porous plug is based on the law of Darcy [15] amended later by Kozeny [16]. Kozeny showed that the flow of a liquid through a plug of particles was inversely proportional to the square of the specific surface, if the porosity, the arrangement of the particles, the dimensions of the meas-

Figure 9 Relationship between image analysis average values of ρ Area and Total Area/ v : (area $\times$ 1.52) = 1.02(total area/0.75); $R^2 = 0.934$; $F(1,103) = 166\,176$; $p = 0.0001$; standard error of estimate = 4.1.

uring chamber and the difference in pressure between the two ends of the sample were constant. The equation of Kozeny applied to the case of an air flow passing through a fiber plug can be written as follows:

$$S_0^2 = \frac{1}{K} \frac{A \Delta P}{\mu L Q} \frac{\epsilon^3}{(1 - \epsilon)^2} \quad (11)$$

where S_0 represents the specific surface of the particles in cm^2/cm^3 , A is the area of the cross-section of the chamber in cm^2 (constant for a given instrument), ΔP is the pressure difference across the ends of the sample in g/cm^2 , μ is the air viscosity at 70°F and 65% relative humidity in 10^{-6} poises (constant), L is the length of the chamber in cm (constant for a given instrument), Q is the air flow in $\text{cm}^3/\text{second}$, K is a constant that depends on the shape and arrangement of the fibers in a given sample (K is equal to K_0/ζ , where K_0 is a factor of the shape of the section of the flow channels and ζ is a constant), ϵ is the porosity or proportion of space unoccupied by material [(chamber volume - cotton volume)/chamber volume].

In 1950, the USDA released a revised micronaire scale [17]. The previous scale was a linear function of the air flow rate. The new scale, still in use today, is curvilinear. In order to convert the current micronaire scale into a linear function of the flow rate, the following quadratic transformation should be used:

$$Y = 2.314 + 0.0413X + 0.101X^2 \quad (12)$$

where Y is the micronaire in the curvilinear scale and X is the micronaire in the linear scale [17].

Figure 10 shows the relationship between HVI micronaire and the linear scale micronaire equivalent. It appears clearly that within the range of interest (HVI micronaire from 3.0 to 5.0) the relationship is essentially linear. Within

Figure 10 Relationship between Micronaire linear scale and HVI micronaire.

this range, the coefficient of determination for a linear relationship is 0.990 whereas it is 0.998 for a quadratic relationship.

The micronaire in the linear scale should be proportional to the air flow at constant ΔP and if one considers K and ϵ constant (which is debatable) then the micronaire in the linear scale should be directly proportional to the inverse of the square of the specific surface.

$$Q = \frac{1}{S_0^2} \frac{A \Delta P}{K \mu L} \frac{\epsilon^3}{(1-\epsilon)^2} = Cst \frac{1}{S_0^2} \quad (13)$$

with $Cst = \text{constant}$.

According to Heap [14], S_0 , the specific surface of individual fibers, is equal to the perimeter of the fiber (equivalent to the area for one unit of length) divided by the area of the cross-section including the lumen (equivalent to the volume for 1 unit of length), thus:

$$S_0 = \frac{P}{\text{TotalArea}} = v \frac{P}{H} \quad (14)$$

The authors have shown that the total area (*Total Area*) of the cross-sections with lumen is proportional to the area of the cross-sections without lumen (*Area*).

Therefore,

$$S_0 \propto P/H \quad (15)$$

$$1/S_0^2 \propto H^2/P^2 = (\rho \text{Area})^2/P^2 \quad (16)$$

$$\text{and } \theta = 4\pi \text{Area}/P^2$$

therefore,

$$P^2 = 4\pi \text{Area}/\theta \quad (17)$$

Then,

$$1/S_0^2 \propto \theta (\rho \text{Area})^2/4\pi \text{Area} = \theta \rho^2 \text{Area}/4\pi \quad (18)$$

$$1/S_0^2 \propto 0.577 M \rho (\rho \text{Area})/4\pi = 0.577 \rho MH/4\pi$$

Therefore, $1/S_0^2$ is directly proportional to MH if ρ is constant.

When one seeks to compare the image analysis data with the micronaire (air flow measurement), the following relationship must be true:

$$\frac{1}{S_0^2} = K \frac{\mu L}{A} \frac{Q}{\Delta P} \frac{(1-\epsilon)^2}{\epsilon^3} \propto \frac{0.577 \rho MH}{4\pi} \quad (19)$$

Therefore, to obtain a perfect relationship between the product MH and the micronaire, K , ϵ , and ρ must be constant, which is not likely. This relationship should probably be linear or should have a very slight curvature. There is good correspondence between our results and the theory (Figure 11).

The averages obtained for the 104 bales (Figure 12) show that, for the measured parameters, the ranges of variation obtained are very broad.

Table 3 shows the expected confidence intervals for 8 and 16 replications of 500 fiber cross-sections. The precision obtained is excellent.

Table 3 Expected confidence intervals for 8 and 16 replications of 500 fiber cross sections.

	8 replications of 500 sections	16 replications of 500 sections
Perimeter	$\pm 0.78 \mu (\pm 1.5\%)$	$\pm 0.55 \mu (\pm 1.0\%)$
Area	$\pm 3.2 \mu^2 (\pm 3.0\%)$	$\pm 2.2 \mu^2 (\pm 2.1\%)$
Theta	$\pm 0.009 (\pm 1.8\%)$	$\pm 0.006 (\pm 1.3\%)$

Figure 11 Relationship between the product MH (from image analysis of cotton fiber cross-sections) and the micronaire. $MH = 39.38 \text{ micronaire} - 22.67$; $R^2 = 0.854$; $F(1,102) = 598.85$; $p = 0.0001$; standard error of estimate = 9.1.

Figure 12 Bale averages for the 104 reference cottons: (a) perimeter, (b) area, (c) total area, (d) theta.

To constitute a good base for the calibration of the indirect measurement instruments for maturity and fineness one should have:

- A broad range of values for perimeter, area and theta.

- Low coefficients of variation of the measurements.
- Low coefficient of determination between maturity and fineness (Figure 13).
- A low coefficient of determination between microaire and maturity ratio for the full range of bales. It can be seen from Figure 14 that it is indeed the case.

Figure 13 Relationship between image analysis maturity ratio ($0/0.577$) and image analysis fineness ($1.52 \cdot \text{area}$). Fineness = $59.144 M + 111.71$; $R^2 = 0.122$; $F(1,102) = 14.11$; $p = 0.0003$; standard error of estimate = 15.1.

Figure 14 Relationship between HVI microaire and image analysis maturity ratio. $M = 0.129 \text{ microaire} + 0.331$; $R^2 = 0.577$; $F(1,102) = 138.87$; $p = 0.0001$; standard error of estimate = 0.06.

Therefore, this population of bales constitutes a good base for the calibration of the indirect measurement instruments for maturity and fineness.

Conclusions

The authors now have 104 reference cottons which will enable them to calibrate double compression testers (Lintronic, CSIRO) and the AFIS (Uster). The calibration of the AFIS will probably be a difficult task. Although calibration could be done on the average values, the main advantage of an apparatus such as the AFIS is to have access to the fiber distributions. This implies the necessity of calibrating the distributions, as well as the averages.

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