NEW DEFINITIONS FOR COTTON FIBER MATURITY RATIO

Xiaoliang Cui
James Rodgers
Chris Delhom
USDA ARS, SRRC
New Orleans, LA

Abstract

The fiber's maturity impacts the fiber's downstream processing and yarn and fabric quality, and therefore is an important cotton quality and processing parameter. The results from this research show that the cotton fiber maturity has positive correlations with fiber cross sectional (or secondary wall) area and weight (or mass). To better characterize the overall maturity of a cotton sample, new concepts and definitions of cotton fiber Maturity Ratio by number, by area, and by weight are introduced. From this small set of test results, on average, the Maturity Ratio by area is about 8% higher than the Maturity Ratio by number, and the Maturity Ratio by weight is about 14% higher than the Maturity Ratio by number. The results also showed that different Maturity Ratios may rank the overall sample maturity differently. The impact of sampling and sample preparation methods on Maturity Ratio results is also discussed. The findings may be more important for cotton breeders in breeding selections.

Introduction

The fiber's maturity can impact the fiber's downstream processing and yarn and fabric quality, and therefore is an important cotton quality and processing parameter. Cotton fiber maturity is often defined as the degree of thickening or development of the fiber's secondary wall (ASTM D123, Wakelyn et al. 2007). There are several methods for measuring maturity and/or fineness, to include the Uster® Advanced Fiber Information System (AFIS), the Fiber Maturity Tester (FMT), Cottonscope® (Rodgers et al. 2012, 2013), polarized light microscopy of longitudinal fibers (Bel and Xu 2010), cross-section image analysis microscopy (IAM) (Thibodeaux and Rajasekaran 1999, Xu and Huang 2004, and Hequet et al. 2006), and spectroscopy (e.g., Near Infrared or NIR) (Montalvo and Von Hoven 2004). Cotton maturity has been a major concern in cotton breeding because fiber maturity regulated by environmental stress is a major factor determining cotton yield and value. Comprehensive functional analyses of a cotton mutant (*im*) having low fiber maturity showed that fiber maturity was controlled by genes and pathways responding to environmental stress (Kim et al. 2013).

To quantitatively characterize the cotton fiber maturity, a few statistical parameters have been defined and used. For example, Maturity M is defined in ASTM D1442 as

$$M = N_1 \div N \times 100\%, \qquad 0 \le M \le 1 \tag{1}$$

Where N_1 is the number of maturity fibers, and N is the total number of fibers.

However, such defined Maturity has shortcomings: a fiber is either mature or immature, but not in-between; it reports only one maturity value of the sample, but no information about maturity distribution.

On the other hand, another parameter for cotton maturity, Theta (θ) or circularity, has been widely used. Theta or circularity (θ) is defined as the wall area A_w divided by the area of a circle having the same perimeter P (Lord and Heap, 1988).

$$\theta = 4\pi A_w/P^2 \qquad 0 < \theta \le 1 \tag{2}$$

Based on Theta, Maturity Ratio MR is defined as:

$$MR = \theta/0.577 \qquad 0 < \theta \le 1.733 \tag{3}$$

Since the difference between fiber circularity and maturity ratio is a constant, a higher circularity value always corresponds to a higher maturity, and we sometimes use the two terms interchangeably below. It can be seen that by such definitions, each individual fiber has a θ_i and an MR_i, and the sample has a maturity distribution. To assess the overall maturity of the sample, the average Maturity Ratio of all fibers is used:

$$MR_{Avg} = \sum MR_i / N = \sum \theta_i / 0.577N \quad (4\text{-a})$$

Where MR_{Avg} is the average Maturity Ratio of the sample, θ_i is the circularity of each individual fiber, N is the total number of fibers of the sample.

However, such defined maturity ratio still has a shortcoming: it cannot accurately assess the overall maturity of a sample, because fiber maturity has positive correlation with fiber secondary wall area and fiber weight, which will be discussed in more detail below. A more accurate quality parameter for sample maturity should be able to reflect the fact that fibers with larger cross section areas and heavier should carry more weight in calculating maturity of the sample.

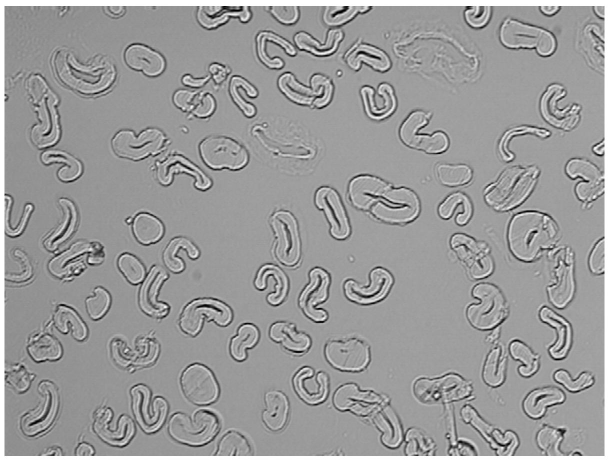

Figure 1. Variation of cotton fiber cross sectional area or secondary wall area

<u>New Definitions for Cotton Maturity Ratio</u>

<u>Maturity Ratio by Number</u>

In calculating the value of MR_{Avg} as above, the Maturity Ratio of each fiber is averaged. To distinguish it from the two new definitions introduced below, we define the as Maturity Ratio by number.

$$MR_N = MR_{Avg} = \sum MR_i / N = \sum \theta_i / 0.577N \quad (4\text{-b})$$

Maturity Ratios reported by image analysis method and AFIS are actually MR_N.

<u>Maturity Ratio by Area</u>

Cotton fiber cross section area or secondary wall area varies, as can be seen from Figure 1. Each fiber contributes to the total maturity of the sample according to its cross section area. Therefore, a more accurate characterization of the overall maturity ratio of a sample should take this into consideration. Therefore, a new concept of cotton fiber maturity ratio by cross section area or wall area is introduced. A individual fiber's maturity ratio by area MR_{iA} is defined as:

$$MR_{iA} = MR_i \times A_i / A_{avg} = (\theta_i / 0.577) \times (A_i / A_{avg}) \quad (5)$$

Where A_i is the cross section area or the secondary wall area of a fiber, A_{avg} is the average wall area of all fibers.

The average fiber maturity by wall area MR_A is defined as

$$MR_A = \sum MR_{iA} \div N = \sum (MR_i \times A_i) \div (A_{avg} \times N) = \sum (MR_i \times A_i) \div A_T \quad (6)$$

Where N is the total number of fibers in the sample, and A_T is the total wall area of all fibers.

It can be seen from Equations 5 and 6 that if a fiber's wall area is larger than the average wall area of all fibers, its maturity ration by area contributes more to the overall maturity ratio, or vice versa.

Maturity Ratio by Weight

Further, a major impact of cotton fiber maturity is on dyeability, which is proportional to the weight or mass of materials to be dyed. Obviously, if two fibers have the same maturity ratio, the heavier fiber affects the dyability than the lighter fiber. An even more accurate characterization of cotton fiber maturity ratio should take this into consideration. Therefore, a new concept of cotton fiber maturity ratio by weight is introduced. An individual fiber's maturity ratio by weight MR_{iW} is defined as:

$$MR_{iW} = MR_i \times (W_i / W_{avg}) = (\theta_i / 0.577) \times (W_i / W_{avg}) \qquad (7)$$

Where W_i is the weight of an individual fiber, W_{avg} is the average weight of all fibers.

The average fiber maturity by weight MR_W is defined as

$$MR_W = \sum MR_{iW} \div N = \sum (MR_i \times W_i) \div (W_{avg} \times N) = \sum (MR_i \times W_i) \div W_T \qquad (8)$$

Where N is the total number of fibers in the sample, and W_T is the total weight of all fibers.

Since we have

$$W_i = A_i \times L_i \times \rho, \qquad (9)$$

where L_i is the length of an individual fiber, and ρ is the density of cellulose, then Equation 8 can be rewritten as

$$MR_W = \sum MR_{iW} \div N = \sum (MR_i \times A_i \times L_i) \div \sum (A_i \times L_i) \qquad (10)$$

Please notice that ρ the density of cellulose is cancelled out in Equation 10, the actual value of ρ does not matter in the calculation of maturity ratio.

Materials and Experiments

A set of 12 cotton samples covering a wide range of Micronaire (Mic) values was selected. Some fiber properties of the selected samples are listed in Table 1. All samples were kept in standard conditions (relative humidity of 65 ± 2% and temperature of 21 ± 1°C) for at least 48 hours, and then tested on an AFIS. The length, θ, and cross section area of each single fiber were saved in the computer and later retrieved to calculate fiber maturity ratios by number, by cross section area and by weight.

Table 1. Selected fiber properties of the samples

Sample ID	*Mic*	*UQL(w)*	θ	*Area*
A	2.72	1.18	0.405	88.4
B	2.52	1.11	0.409	94.8
C	3.54	1.15	0.435	104.7
D	3.51	1.23	0.431	98.5
E	4.05	1.17	0.442	109.6
F	3.98	1.13	0.450	104.2
G	4.50	1.24	0.461	112.7
H	4.46	1.11	0.468	108.1
I	5.48	1.03	0.481	124.3
J	5.02	1.14	0.493	116.7
K	5.44	1.19	0.496	124.7
L	5.03	1.17	0.499	118.4

Results and Discussion

Correlations among fiber maturity, cross section area, and weight

The statistical analysis of the AFIS test results showed that there exist strong positive correlations among fiber maturity, cross section area and weight, indicating more mature fibers tend to be thicker and heavier. Figure 2 shows typical scatter plots of fiber maturity vs. area (four different samples). The scatter plot charts for fiber maturity vs. weight show similar pattern for all samples (not shown here). Table 2 lists the correlation coefficients among fiber maturity, cross section area and weight. The results show that fiber maturity has positive correlation coefficients with cross section area and fiber weight, indicating thicker and heavier (longer and/or thicker) fibers tend to be more mature. These facts prove that fiber maturity by area and weight can more accurately characterize a sample’s overall maturity property.

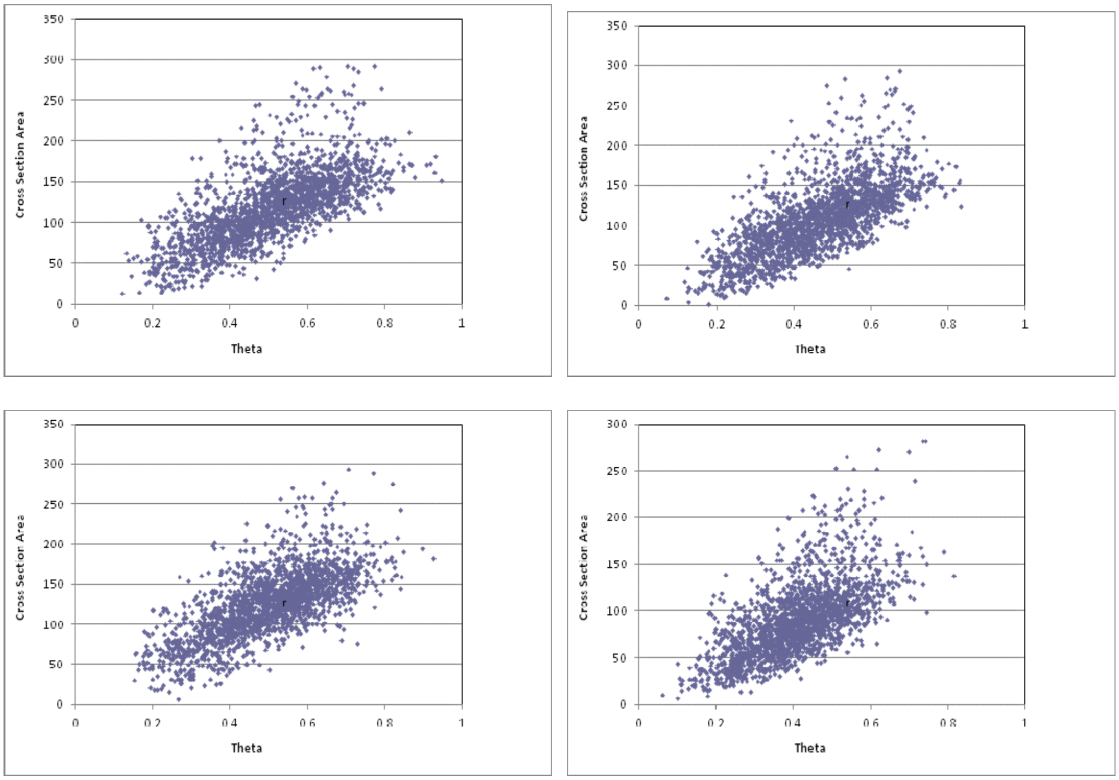

Figure 2. Typical scatter plots of fiber maturity vs. cross section (secondary wall) area.

Table 2. Correlation coefficients among fiber maturity, area, and weight

Sample ID	*Theta vs. Area*	*Theta vs. Weight*
A	0.638	0.707
B	0.646	0.698
C	0.674	0.715
D	0.676	0.738
E	0.677	0.720
F	0.673	0.736
G	0.681	0.720
H	0.691	0.741
I	0.725	0.725
J	0.718	0.747
K	0.690	0.739
L	0.693	0.741

Maturity Ratios by Number, Area, and Weight

From the AFIS single fiber data, the maturity ratios by number, by area, and by weight were calculated. The results were listed in Table 3, arranged by the increasing order of MR by number. On average, the Maturity Ratio by area is about 8% higher than the Maturity Ratio by number, and the Maturity Ratio by weight is about 14% higher than the Maturity Ratio by number.

Table 3. Calculated maturity ratios by number, by area, and by weight

Sample ID	*MR by number*	*MR by Area*	*MR by Weight*
A	0.769	0.830	0.880
B	0.779	0.839	0.885
C	0.803	0.868	0.933
D	0.809	0.880	0.956
E	0.827	0.890	0.933
F	0.850	0.911	0.954
G	0.855	0.915	0.979
H	0.868	0.942	0.998
I	0.896	0.962	1.028
J	0.927	0.994	1.048
K	0.937	0.994	1.069
L	0.949	1.019	1.090
Avg.	0.856	0.920	0.979
Difference (%)		7.952	14.451

We reordered the results by the Maturity Ratio by area values, and the samples showed the same rank as ordered by Maturity Ratio by Area. While we reordered the results by the Maturity by weight, the rank changed, as can be seen from Table 4. This indicates that different Maturity Ratios may rank the overall sample maturity differently. This may be more important for cotton breeders in breeding selections.

Table 4. Calculated maturity ratios by number, by area, and by weight reordered by increasing MR by weight

Sample ID	*MR by number*	*MR by Area*	*MR by Weight*
A	0.769	0.830	0.880
B	0.779	0.839	0.885
C	0.803	0.868	0.933
E	0.827	0.890	0.933
F	0.850	0.911	0.954
D	0.809	0.880	0.956
G	0.855	0.915	0.979
H	0.868	0.942	0.998
I	0.896	0.962	1.028
J	0.927	0.994	1.048
K	0.937	0.994	1.069
L	0.949	1.019	1.090
Avg.	0.856	0.920	0.979
Difference (%)		7.952	14.451

This study revealed the positive relationships among fiber maturity, area, and weight. Since fiber weight is determined by the cross sectional area and fiber length, the fiber maturity is positively related to fiber length. This indicates that the sampling and sample preparation methods impact the test results. Take image analysis of fiber cross sections for example, if the image is taken from cutting a sliver, the sample is biased by fiber length, because the possibility of a fiber to be in the image is proportional to its length. As so, any image contains a higher number of longer fibers than shorter fibers. For a different sampling scenario, if all specimen fiber are aligned at one end of each and if the image is taken from cutting fibers at the aligned line, the sample is number biased, because every fiber, no matter longer or shorter, has equal possibility to be included in the image. Obviously, the first image contains a higher number of longer fibers than that in the second image. Because the positive relationship, the Maturity Ratio calculated from the first image will be higher than that from the second image. The test method for maturity of ASTM D1442 (ASTM 2012) pointed out that different sampling method may lead to a few percentage difference in calculated maturity ratio values, but did not give an explanation. The relationships revealed in the study actually provide, at least partially, an explanation for it.

The sample set in this study is small, only including 12 samples. More samples need to be tested to obtain more general information on relationships among Maturity Ratios by number, by area, and by weight, as well as to obtain the relationships of these different maturity ratios with other fiber properties, especially the outlier samples. Further work is also needed to find the usefulness of these different maturity ratios in predicting yarn and fabric properties.

Summary

The research results showed that the cotton fiber maturity has positive correlations with fiber cross sectional (or secondary wall) area and weight (or mass). Because of this correlation, sampling and sample preparation methods affects the Maturity Ratio results. To better characterize the overall maturity of a cotton sample, new concepts and definitions of cotton fiber Maturity Ratio by number, by area, and by weight are introduced. Based on the test results, on average, the Maturity Ratio by area is about 8% higher than the Maturity Ratio by number, and the Maturity Ratio by weight is about 14% higher than the Maturity Ratio by number. The results also show that different Maturity Ratios may rank the overall sample maturity differently.

Acknowledgements

The authors would like to acknowledge the assistance of Miss. Melissa Dunn with the testing.

Disclaimer

Names of companies or commercial products are given solely for the purpose of providing specific information; their mention does not imply recommendation or endorsement by the U.S. Department of Agriculture over others not mentioned.

References

ASTM Standard D123-13a, Standard Terminology Relating to Textiles, ASTM International, West Conshohocken, PA, 2013.

ASTM D1442-06 (2012), Standard Test Method for Maturity of Cotton Fibers (Sodium Hydroxide Swelling and Polarized Light Procedures), ASTM International, West Conshohocken, PA, 2012.

Bel, P. and Xu, B., Fiber Longitudinal Measurements for Predicting White-Speck Levels of Dyed Cotton Fabrics, Textile Research Journal, 80(11), 1047-1055, 2010.

Hequet, E., Wyatt, B., Abidi, N., and Thibodeaux, D. P., Creation of a Set of Reference Material for Cotton Fiber Maturity Measurements, Textile Research Journal, vol. 76 no. 7, 576-586, 2006.

Kim, H.J., Tang, Y., Moon, H.S., Delhom, C.D., Fang, D.D. Functional analyses of cotton (*Gossypium hirsutum* L.) immature fiber (*im*) mutant infer that fiber cell wall development is associated with stress responses. BMC Genomics. 14,889, 2013.

Lord, E., and Heap, S. The origin and assessment of cotton fiber maturity. International Institute for Cotton, Manchester, UK, 38 pp, 1988.

Montalvo, J., and Von Hoven, T. Chapter 25: Analysis of Cotton. Near-Infrared Spectroscopy in Agriculture. Eds. C. Roberts, J. Workman, and J. Reeves. Madison, WI: American Society of Agronomy, Agronomy Monograph No. 44, 671-728, 2004.

Rodgers III, J.E., Delhom, C.D., Thibodeaux, D.P. Rapid cotton maturity and fineness measurements using the Cottonscope®. National Cotton Council Beltwide Cotton Conference. p.1228-1232. 2012.

Rodgers III, J.E., Delhom, C.D., Hinchliffe, D.J., Kim, H.J., Cui, X. A rapid measurement for cotton breeders of maturity and fineness from developing and mature fibers. Textile Research Journal. 83(14):1439-1451. 2013.

Thibodeaux, D. P., Rajasekaran, K., Development of New Reference Standards for Cotton Fiber Maturity, The Journal of Cotton Science 3:188-193, 1999.

Wakelyn, P., Bertoniere, N., Edwards, J., French, A., Gamble, G., et. al. Chapter 7: Cotton Fiber Chemistry and Technology. CRC Press, Boca Raton, FL, 107-109, 2007.

Xu, B. and Huang,Y., Image Analysis for Cotton Fibers, Part II: Cross-Sectional Measurement, Textile Research Journal, 74(5), 409-416, 2004.