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TEXTILE TECHNOLOGY

Relationships Between Micronaire, Fineness, and Maturity. Part II. Experimental

Joseph G. Montalvo, Jr.* and Terri M. Von Hoven

ABSTRACT

In Part I of this series, models were developed and computer simulated to understand the variability in coefficients of determination (R^2) between fineness and maturity, micronaire and fineness, and micronaire and maturity of cotton (*Gossypium hirsutum* L.). All plots of the simulated fiber properties produced families of lines rather than a single line because biological or cross-sectional perimeter plays a significant role in interpretation of the relationships. To enhance the R^2 values, this paper revisits the Part I simulation database to obtain information about how to derive diagnostic relationships to fit to a simple linear model. These new expressions incorporate perimeter in the model in a way that families of lines give a single line plot. The diagnostic criteria for fitting data to a model are that plots of the data yield a single line with a high R^2 and with predictable slope and intercept values. A fit of the data provides a proof for the Lord equation for micronaire and for the definitions of fineness and maturity in equation form. It is of special significance that the definitions of fineness and maturity are independent of the experimental methods of measurement and independent of the Lord equation. The diagnostic models were tested on 305 cottons with experimental data produced by the Southern Regional Research Center (SRRC) upgraded Fineness and Maturity Tester (FMT). For all of the diagnostic relationships, plots of the FMT data produced a single line with a high R^2 and with slopes and intercepts that conform to simulation predictions.

Part I of this series concentrated on the development of models and their computer simulation to understand the variability in coefficients of determination (R^2) between the fiber properties of micronaire and fineness, micronaire and maturity, and fineness and maturity (Montalvo, 2005). All three properties are unique combinations of wall area and perimeter. The specific combinations of wall area and perimeter for fineness, maturity, and micronaire are wall area, wall area divided by perimeter squared, and the ratio of wall area and perimeter, respectively. Wall area is a combination of wall thickness squared and perimeter (Montalvo, 1991).

When graphing fineness, maturity, and micronaire as a function of wall thickness, a family of curved lines was observed in which each line represents a given perimeter value (Montalvo, 2005). In contrast, similar plots of fineness and maturity, micronaire and fineness, and micronaire and maturity give a family of linear lines. These families of lines confounded the interpretation of the coefficients of determination.

An R^2 represents the variance in fitting data to a least squares model. For example, if an inappropriate model is chosen, a single line for a data set comprising a series of lines, then the R^2 will be reduced. A low R^2 does not indicate there is no relationship between the two variables; it is simply indicative of a poor fit of the data to the specific model being applied.

In Part II of the series, there are several specific objectives related to the simulated families of lines between fineness and maturity, micronaire and fineness, and micronaire and maturity. The first objective is to use the Part I simulation database and create diagnostic equations that transform a multi-line plot to a simple linear model; therefore, improving the R^2 values. The remaining two objectives are concerned with testing the experimental data produced with the FMT. Families of lines are established between the measured fiber properties, and a fit of the experimental data on 305 cottons to the diagnostic relationships is illustrated.

MATERIALS AND METHODS

Cottons. Cotton samples exhibiting a wide range of micronaire values were obtained from U.S. and international collaborators. The full set of 305 samples was received as 10 separate shipments each from a different collaborator over several years. The number

J. G. Montalvo, Jr. and T. M. Von Hoven, USDA/ARS; Southern Regional Research Center, P.O. Box 19687, New Orleans, LA 70124
*Corresponding author: montalvo@srrc.ars.usda.gov

of samples in each shipment (subset) ranged from 9 to 54. All cottons were cleaned with two passes in a Shirley Analyzer, except for a small number that had been cleaned by the collaborators.

SRRC upgraded FMT. Cleaned cotton samples were analyzed on the FMT (089 Micromat Tester, Shirley Developments Ltd.; Stockport, England) that had been upgraded at the Southern Regional Research Center (SRRC). The FMT is a double compression airflow device that measures the pressure drop of air drawn through a 4-g sample that is compressed to two different densities during the test. The initial and second stage pressure drops are referred to as *PL* and *PH*, respectively, and are converted to micronaire, fineness, maturity, and perimeter by appropriate empirical equations (SDL manual, 1994; Montalvo and Grimball, 1994). The FMT equations were calibrated against the British Standard Methods and image analysis (Von Hoven et al., 2001; Thibodeaux and Evans, 1986). The software (Montalvo and Grimball, 1994) has been distributed worldwide and presented at numerous FMT workshops in the USA and abroad.

The most important features of our revisions to the FMT are the sealing of the air flow system, the installation of a leak detector module, and the use of physical standards, dubbed headspace resistance standards (Montalvo and Faught, 1999; Montalvo et al., 2001; Von Hoven et al., 2001). Calibration is a three step process. The calibration order is detector, air flow system, and sample chamber volume. The detector is used to calibrate the other instrumental settings, and the air flow system is needed to calibrate the chamber volume. Calibration details have been presented elsewhere (Von Hoven et al., 2001). Results on the upgraded FMT are more accurate and precise compared with results before upgrading.

During testing, a strict quality control protocol was followed that included physical standards that mimic mid-micronaire cotton. For each cotton, six replications of 4-g fiber samples were carded using Louette cotton hand cards with 100 picks per 2.54 cm (1.0 in). The carded sample was then rolled into a sliver with a diameter of approximately 5.0 cm (2.0 in) and inserted into the FMT with a specially designed mechanical device (Montalvo and Von Hoven, 2003).

All statistical analysis was by Microsoft Excel 2000 data analysis software (Microsoft Corporation; Redmond, WA). Micronaire, fineness, maturity, and perimeter values were computed by equations from the two pressure drops (*PL* and *PH*) produced by the FMT on each specimen analyzed (SDL manual, 1994; Montalvo and Grimball, 1994). Means were calculated from the six replications for each cotton and were used in plotting the data.

RESULTS AND DISCUSSION

Model relations from Part I. In Table 1, a list of equations from Part I of this research (Montalvo, 2005), which are pertinent to this paper, is presented with corresponding equation numbers. Equations 3 and 5 follow directly from the definitions of the parameters assuming that the density of the cell wall is 1.52 g/cm^3 (Ramey, 1982). Equations 7 and 8 involve the added assumption that the instrument constants, the experimental conditions, and the arbitrary transformation built into the micronaire scale are unvarying in nature (Heap, 2000).

Table 1. Equations used to develop model relations in Part I of this research that are pertinent to Part II [z]

$H = 1.52\,A_w = 1.52T(P - \pi T) = 1.52TP - 1.52\pi T^2$	**[Eq. 3]**
$M = \dfrac{\theta}{0.577} = \dfrac{4\pi A_w}{0.577P^2} = \dfrac{4\pi T(P - \pi T)}{0.577P^2}$	**[Eq. 5]**
$Mic = 0.509\sqrt{(MH + 8.359)} - 2.352 = 2.929\sqrt{\dfrac{(A_w)^2}{P^2} + 0.2525} - 2.352$	**[Eq. 7]**
$Mic = 2.929\sqrt{(\dfrac{T^2(P - \pi T)^2}{P^2} + 0.2525)} - 2.352$	**[Eq. 8]**

Family of lines	
y-axis	**x-axis**
H	***M***
Mic	***H***
Mic	***M***

[z] *H* = fineness (mtex), A_w = wall area (μm^2), *T* = wall thickness (μm), *P* = perimeter (μm), *M* =maturity ratio, θ = theta, and *Mic* = micronaire. Source for the equations are as follows: Eq. 3, (Ramey, 1982; Montalvo, 1991); Eq. 5, (Lord and Heap, 1988); Eqs. 7 and 8, [Lord, 1956; Montalvo, 2005 (Part I of this series)].

Diagnostic Equations

Diagnostic equations developed in this study are listed in Table 2. The equation numbers are a continuation of the sequence in Part I. The derivations for Eqs. 14, 15, and 16 are rigorous. All three equations are derived by algebra, and the resulting coefficients in the models were confirmed by regression of the Part I simulation database.

Algebra approach. Equation 14 is derived explicitly from algebra manipulations of Eqs. 3 and 5. To derive Eq. 15, Eq. 3 is substituted into the second form of Eq. 7 to give the square root term, $((H/1.52P)^2 + 0.2525)^{0.5}$, which is linearly transformed to (0.6356H/P + 0.133; $R^2 = 0.9999$) using only *H* and *P* values simulated in Part I. The new term is substituted into Eq. 7 and gives Eq. 15. Equation 16 is derived explicitly from algebra manipulations of Eqs. 14 and 15, so it is not an independent diagnostic test.

Confirmation of coefficients. Do the numerical coefficients (a and b) in Table 2 that were derived by algebra agree with the coefficients (a' and b') produced by linear regression of the Part I simulation database? All paired combinations of the parameters, *H*/*P* and *MP*; *Mic* and *H*/*P*; and *Mic* and *MP,* were tested by regression of the database. For the present simulations, the same range of values for fineness, perimeter, and maturity was used.

The resultant simulation plots between *H/P* and *MP*, *Mic* and *H*/*P*, and *Mic* and *MP*, demonstrate a simple straight line ($R^2 = 1$) in all cases (Table 2). The regression coefficients (a' and b') agree well with the algebraic (a and b) values. There are interesting trends in the coefficients. For the *H/P* diagnostic model (Eq. 14), the intercept value is zero and about -1.96 for the other two models. Note that the slope for each equation is different, that is the slope for Eq. 14 ≈ 0.0698; for Eq. 15 ≈ 1.86; and for Eq. 16 ≈ 0.130.

Diagnostic criteria. Of the three diagnostic models, $H/P = aMP$ (Eq. 14), is perhaps the most important, because it is based solely on the definitions of fineness and maturity (Eqs. 3 and 5) rather than empirical results associated with the micronaire model. This means that Eq. 14 is independent of the experimental method by which the fiber property data is produced. Thus, the diagnostic criterion for a fit of the measured values is that a plot of *H/P* (y-axis) versus *MP* must produce a single straight line. The intercept of the line should be zero and the slope close to 0.0698, or the experimental data does not conform to the definitions of fineness and maturity.

The diagnostic criterion for a fit to experimental data by Eq. 15 is that a plot of *Mic* (y-axis) versus *H/P* must produce a single straight line. The intercept should be about -1.96 and the slope near 1.86, or the measured values do not conform to the underlying models. Similarly, a diagnostic criterion statement can be written to describe a fit of experimental data to Eq. 16.

Because *Mic* is common to Eqs. 15 and 16, it can be canceled out by combining the equations. As a consequence, the ratio of the regression slopes of Eq. 15 to Eq. 16 is 14.327, and the reciprocal is equal to 0.0698, the slope of Eq. 14. Stated another way, the slope of Eq. 15 multiplied by the slope of Eq. 14 divided by the slope of Eq. 16 is equal to one and provides additional diagnostic criteria to test experimental data. It should be noted that the test provided in this paragraph is not another independent test but simply an alternative approach.

Graphic Analysis of FMT Data

Descriptive statistics. All of the fiber properties of interest were computed with the FMT algorithms (Table 3) (SDL manual, 1994; Montalvo and Grimball, 1994). Table 4 depicts the minimum, maximum, mean, standard deviation, and coefficient of variation (CV) of the four fiber properties as measured by the FMT. The observed range of values is consistent with the fiber origin (worldwide; Egyptian to short staple coarse) (Ramey, 1982; Lord and Heap, 1988). This means that the wide range of values of the FMT data set provides for rigorous testing of the diagnostic models.

Family of lines plots. The models used to generate the simulated data in Part I of this series, along with the designated parameters assigned to the y-axis and

Table 2. Diagnostic models developed by regression of simulation data from Part I

Model [z]	Algebra		Regression ($R^2 = 1$)		Equation #
	a	b	a'	b'	
$\frac{H}{P} = aMP$	**0.06979**	**0**	**0.06979**	**0**	**[Eq. 14]**
$Mic = a\left(\frac{H}{P}\right) + b$	**1.862**	**-1.963**	**1.864**	**-1.969**	**[Eq. 15]**
$Mic = aMP + b$	**0.1299**	**-1.963**	**0.1301**	**-1.969**	**[Eq. 16]**

[z] ***Mic*** **= micronaire,** ***H*** **= fineness (mtex),** ***P*** **= perimeter (μm), and** ***M*** **= maturity ratio.**

the x-axis in plots for that study, are shown in Table 1. The plots of the simulated fiber properties produced a family of lines between fineness and maturity, micronaire and fineness, and micronaire and maturity.

Table 3. Graphic analysis of fiber properties based on FMT models[z]

$$H = 60000\left(\frac{PH^{1.75}}{PL^{2.75}}\right) \quad [17]$$

$$M = 0.247\left(\frac{PL^{2.125}}{PH^{2}}\right) \quad [18]$$

$$Mic = 0.6 + \frac{850}{(PL + 40)} \quad [19]$$

$$P = 1865.64\frac{PH^{1.875}}{PL^{2.4375}} \quad [20]$$

Family of lines		Single line (diagnostic)	
y-axis	x-axis	y-axis	x-axis
H	*M*	*H/P*	*MP*
Mic	*H*	*Mic*	*H/P*
Mic	*M*	*Mic*	*MP*

[z] ***H*** **= fineness (mtex),** ***M*** **= maturity ratio,** ***Mic*** **= micronaire,** ***P*** **= perimeter (µm),** ***PL*** **= first stage pressure drop (mm water), and** ***PH*** **= second stage pressure drop (mm water).**

Table 4. Descriptive statistics of fiber properties measured by the FMT (N = 305)

Statistic	Fiber property[z]			
	H	*M*	*Mic*	*P*
Minimum	111	0.486	1.96	45.0
Maximum	254	1.11	5.92	64.7
Mean	174	0.864	4.06	53.8
Std. dev.	25.5	0.117	0.749	3.33
CV (%)	14.7	13.5	18.4	6.19

[z] ***H*** **= fineness (mtex),** ***M*** **= maturity ratio,** ***Mic*** **=micronaire, and** ***P*** **= perimeter (µm).**

Does the FMT data produce similar family of lines plots? Are these FMT plots consistent with the relative R^2 of the simulated data plots? The designated parameters assigned to the y-axis and the x-axis in plots of the FMT data are shown in Table 3.

Figures 1 to 3 depict the plotted data for the full sample set (N = 305). In ascending order, the coefficients of determination (R^2) for fineness versus maturity, micronaire versus maturity, and micronaire versus fineness are 0.3796, 0.7532, and 0.8472, respectively. The relative order of the R^2 values for these plots is consistent with the simulated data findings in Part I.

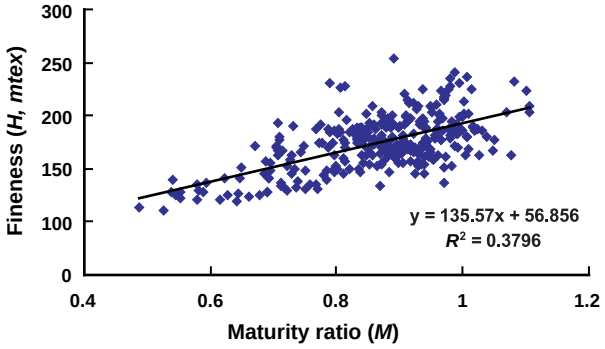

Figure 1. Regression of fineness versus maturity ratio (N = 305).

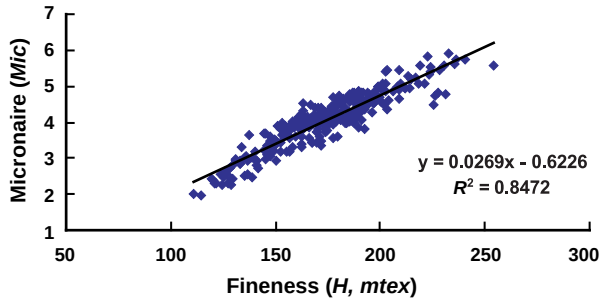

Figure 2. Regression of micronaire versus fineness (N = 305).

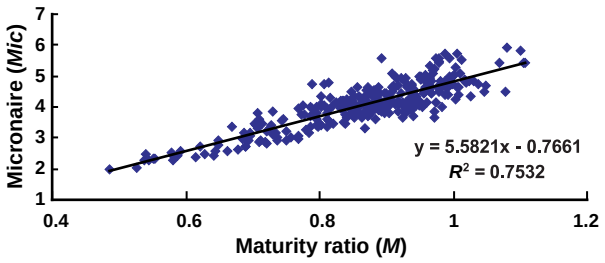

Figure 3. Regression of micronaire versus maturity ratio (N = 305).

Can the three FMT plots be de-convoluted to prove the underlying existence of families of lines rather than scatter in the data? Assuming that perimeter plays a significant role in interpretation of the plotted data in Figures 1, 2, and 3, which are based on airflow measurements, then it should be possible to de-convolute the data by sorting according to perimeter and then plotting a small range of values. Figures 4, 5, and 6 depict example de-convolutions of the FMT plots. Two groups of the data in which the measured perimeters were 50 to 52 µm and 56 to 58 µm demonstrate a family of linear lines. The relative order of the lines for the micronaire versus fineness data is reversed compared with the other

families of lines. This is consistent with the modeling results in Part I.

Ten subsets make up the full set of 305 cottons, and the range of subset R^2 values is dramatic for the *H* and *M,* and the *Mic* and *M* correlations (Table 5). The ranges of R^2 for *H* and *M*, *Mic* and *M*, and *Mic* and *H*, were 0.0442 to 0.9165, 0.3270 to 0.9760, and 0.7640 to 0.9807, respectively. The subsets were analyzed in the FMT in the order received. The R^2 values are not dependent on subset order.

The results in Table 5 are an example of simple linear regression applied to data between two variables when the underlying relationships are more correctly described by families of lines. As a consequence, the R^2 values are highly variable.

Table 5. Dependence of R^2 on sample subset

Subset [y]	Number of samples	R^2 [z]		
		H and *M*	*Mic* and *M*	*Mic* and *H*
3	36	0.0442	0.3270	0.8490
9	45	0.1586	0.5144	0.8528
8	26	0.2683	0.6652	0.7640
4	54	0.3888	0.7538	0.8613
7	9	0.5361	0.8115	0.9124
2	35	0.6351	0.8798	0.9104
5	21	0.6479	0.8399	0.9498
6	37	0.7383	0.9092	0.9402
1	12	0.7387	0.9320	0.9130
10	30	0.9165	0.9760	0.9807
All samples	305	0.3796	0.7532	0.8472

[y] Subset number refers to sequential shipments of samples to SRRC.

[z] *H* = fineness (mtex), *M* = maturity ratio, and *Mic* = micronaire. R^2 values in the *H* and *M* column were sorted in ascending order.

Diagnostic plots. The de-convolution of the FMT family of lines plots (Fig. 4, 5, and 6) indicated perimeter plays a significant role in interpretation of Figures 1, 2, and 3. The diagnostic model plots (Fig. 7, 8, and 9; axis assignments are in Table 3) are intended to transform the family of lines plots into a simple linear plot with an enhanced R^2.

Simple linear plots are observed with all three diagnostic relations. The high coefficients of determination are noteworthy and are the result of (a) the nature of the Lord equation and the FMT algorithms for calculation of the parameters from the two pressure drop measurements (Heap, 2000), (b) the worldwide range of the cottons, (c) the FMT values are the averages of six replicates per cotton, and (d) the fact that each sample was inserted into the instrument's sample chamber in a controlled, reproducible fashion with a mechanical device (Montalvo and Von Hoven, 2003).

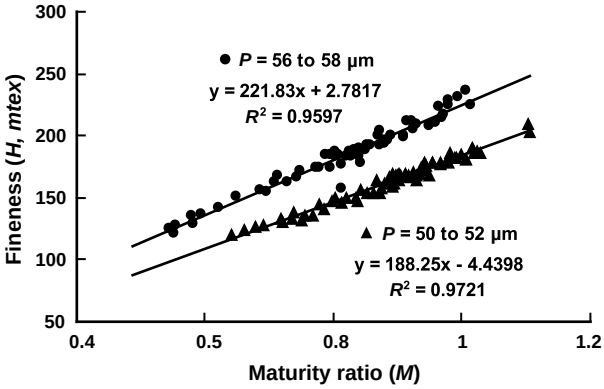

Figure 4. Regression of fineness and maturity ratio for perimeters (*P*) between 50 to 52 µm and 56 to 58 µm, respectively.

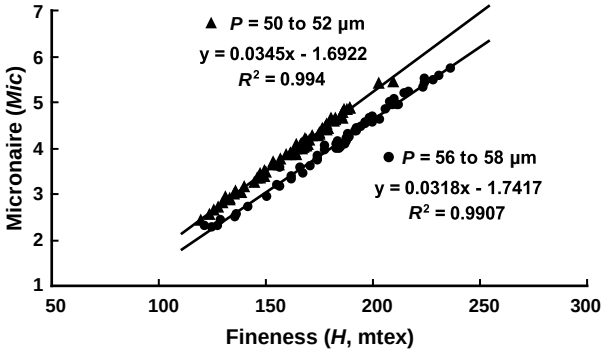

Figure 5. Regression of micronaire and fineness for perimeters (*P*) between 50 to 52 µm and 56 to 58 µm, respectively.

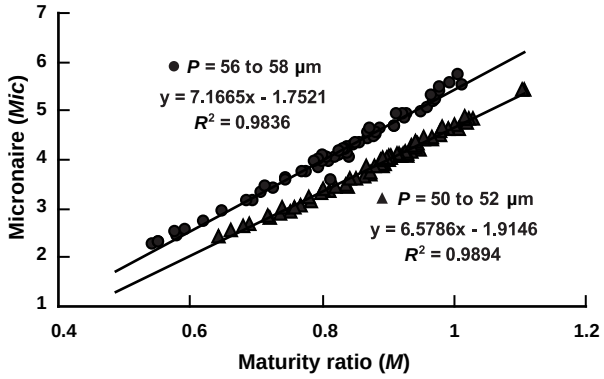

Figure 6. Regression of micronaire and maturity ratio for perimeters (*P*) between 50 to 52 µm and 56 to 58 µm, respectively.

Forcing the line to pass through the origin in Figure 7 allows for comparison of the slopes from the experimental and simulated data, which are in excellent agreement (Table 2). The regression coefficients in Figures 8 and 9 are in good agreement with the simulation results. In Figure 8, the regression coefficients are 1.7778 and -1.6914 compared to the simulation values of 1.864 and -1.969; and in Figure 9, the coefficients are 0.125 and -1.7333 compared to the simulation values of 0.1301 and -1.969. Finally, the ratio of regression slopes in Figure 8 to Figure 9 is 14.22 compared to the simulation value of 14.33. The slope of Figure 8 multiplied by the slope of Figure 7 divided by the slope of Figure 9 is 0.991 compared to the simulation value of 1.0.

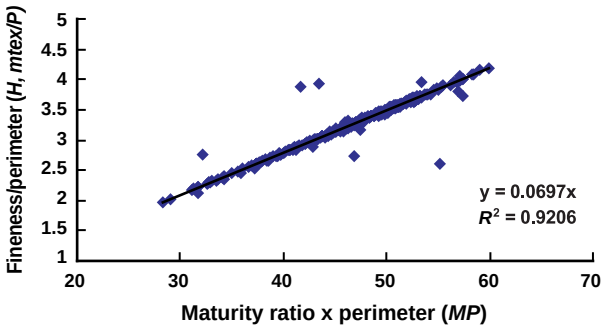

Figure 7. Demonstration of the fit of the experimental data (N = 305) by diagnostic model between fineness/perimeter and maturity ratio x perimeter.

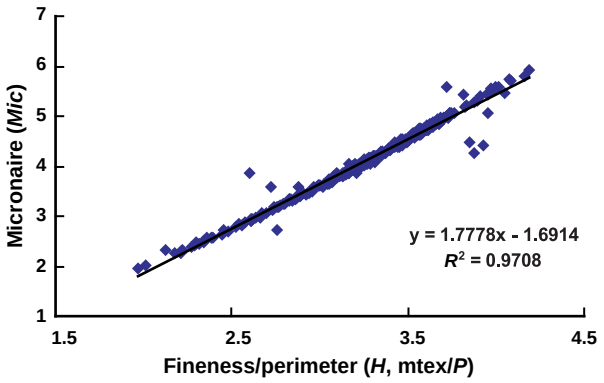

Figure 8. Demonstration of the fit of the experimental data (N = 305) by diagnostic model between micronaire and fineness/perimeter.

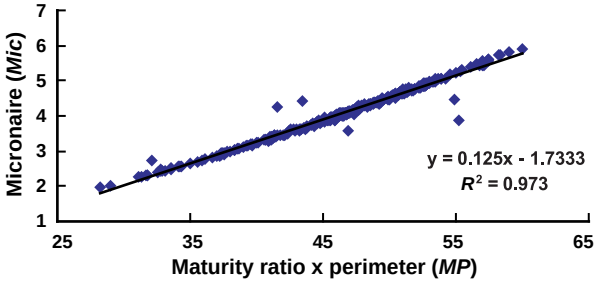

Figure 9. Demonstration of the fit of the experimental data (N = 305) by diagnostic model between micronaire and maturity ratio x perimeter.

The small number of cottons that deviate from the fitted lines in Figures 7, 8, and 9 is noteworthy and also resulted in the wide range R^2 within the subsets (Table 6). The samples gave aberrant results that persisted among the six different test specimens for each cotton. All other cottons gave results in accordance with expectation. Lord and Heap (1988) reported similar findings between the FMT values and direct fiber test results by the British Standard Methods (Von Hoven et al., 2001). They concluded the discrepancies arise from small variations in other fiber features that have not been identified.

Table 6. Dependence of diagnostic equations R^2 on sample subset

Subset [y]	Number of samples	R^2 [z]		
		H/P and *MP*	*Mic* and *MP*	*Mic* and *H/P*
3	36	0.9931	0.9958	0.9946
9	45	0.8151	0.9543	0.9372
8	26	0.9982	0.9485	0.9439
4	54	0.9970	0.9957	0.9955
7	9	0.0186	0.4275	0.7012
2	35	0.8305	0.9509	0.9499
5	21	0.9986	0.9985	0.9980
6	37	0.9926	0.9972	0.9888
1	12	0.9684	0.9967	0.9732
10	30	0.9668	0.9914	0.9913
All samples	305	0.9206	0.9730	0.9708

[y] **Subset number refers to sequential shipments of samples to SRRC. Subset order is comparable to Table 5.**

[z] ***H* = fineness (mtex), *P* = perimeter (μm), *M* = maturity ratio, and *Mic* =micronaire.**

Practical Use

The technology in this series of papers allows for the first time the fitting of micronaire, fineness, and maturity data to diagnostic models that incorporate perimeter into the formula to enhance R^2 values. Three diagnostic models were developed. One (Eq. 14) is based on the definitions of fineness and maturity, while

the other two, Eqs. 15 and 16, include micronaire. There are three variables in each model. A good fit of data to a model is characterized by a high R^2 and slope and intercept values consistent with values in Table 2. To illustrate further the practical use of the technology, the authors present detailed examples related to interpretation of the R^2 between fineness and maturity for several of the 10 sample subsets.

Example one. Consider the R^2 between H and M in sample subsets #3 and #10 (Table 5). The R^2 between H and M is only 0.0442 in subset #3 compared to 0.9165 in subset #10. In contrast, the diagnostic model provided by Eq. 14 produced a high R^2 (Table 6) and a slope consistent with a good fit of data to the model for both subsets.

Examination of the perimeter distributions of the two subsets shows that the ranges and mean values are about the same (Table 7). But the standard deviation and sample variance show significant differences. The standard deviation of perimeter values for subset #3 is larger, that is the average spread in perimeter values is larger, so it has a bigger influence on the data and results in lower R^2 values.

Table 7. Descriptive statistics of perimeter (μm) distribution in two sample subsets

Statistic	Perimeter statistics	
	Subset # 3	Subset # 10
Minimum	47.2	46.6
Maximum	57.4	56.0
Range	10.2	9.41
Mean	52.2	51.8
Standard deviation	2.67	1.68
Sample variance	7.11	2.82
Number of samples	36	30

The collaborator who provided subset #3 was contacted, and informed us that each member (sample) in the subset represented a different cultivar of cotton. The perimeter or biological fineness of a fiber is a characteristic of the cotton cultivar (Ramey, 1982), so a relatively flat distribution of perimeters is expected.

As a consequence of the flat distribution, the R^2 between H and M for subset #3 is only 0.0442, because the 'true' relationship is really a family of lines, each at a constant perimeter. This means that a plot of H versus M is the wrong linear regression model to apply to the data. The diagnostic model given by Eq. 14 is the correct equation to use and, as a result, the R^2 is 0.9931 (Table 6).

Example two. This example deals with subset #4 (Table 5). In the initial screening of this subset with the diagnostic model given by Eq. 14, an R^2 of only 0.664 was obtained. Upon further examination it was discovered that errors had been made in pasting the perimeter values to the Excel file used to generate the plots. After correction the R^2 was 0.997 (Table 6). This ability to rapidly screen the data for poor coefficients of determination resulting from systematic errors in data manipulation is an unexpected benefit of the diagnostic models.

CONCLUSIONS

Plots of FMT data between fineness and maturity, micronaire and fineness, and micronaire and maturity gave a family of lines each representing a fixed perimeter value. Coefficients of determination of the data are confounded by the family of lines in the plots. When a simple linear model was applied to each subset (by source) of samples in the set of 305 cottons, then the R^2 range between fineness and maturity; micronaire and maturity, and micronaire and fineness was 0.0442 to 0.9165, 0.3270 to 0.9760, 0.7640 to 0.9807, respectively. These findings are consistent with the simulation predictions in Part I of this series.

The simulations are revisited in this study to glean information about how to stabilize and enhance the coefficients of determination. Diagnostic relationships were then derived to fit the simulation data to a simple linear model. These relationships include perimeter in the expressions in a way that families of lines give a single line. When applied to the FMT data, the new expressions gave R^2 values for the full set of cottons that ranged from 0.9206 to 0.9730. The high coefficient of determination, slope, and intercept of the diagnostic plots conform to the simulation predictions.

Additional simulations have been performed with added random and systematic error. It is possible to view the departures from the ideal plots and unravel the effects of the total error on the coefficients of determination. This will be reported in Part III.

DISCLAIMER

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imply approval or recommendation of the product to the exclusion of others that may be suitable.

ACKNOWLEDGMENTS

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