ESTIMATION OF HVI BUNDLE MODULUS AND TOUGHNESS AS DETERMINANTS TO TENSILE PROPERTIES OF SPUN YARNS

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Abstract

A new method has been developed for estimating the modulus and toughness of cotton fiber bundles directly from the HVI tenacity-elongation curves. The bundle modulus and toughness were obtained for 36 U. S. Upland cottons from the 1995 crop. The HVI properties including bundle modulus and toughness, Mantis® single fiber tensile properties and yarn tenacities were analyzed to evaluate the relationship among fiber , bundle and yarn properties. The single fiber tensile properties were shown to be translated well into the bundle tensile properties. The single fiber breaking elongation was found to be the most significant contributing factor to bundle tensile properties. The bundle breaking elongation and toughness were shown to increase as the single fiber breaking elongation increased. The bundle modulus increased as the single fiber breaking elongation and/or standard deviation of single fiber breaking elongation decreased.

For predicting the yarn tenacities, the HVI tenacities, standard deviation (S. D.) of single fiber breaking elongation and HVI modulus were all found to be significant contributing factors. The HVI micronaire, tenacities, modulus and toughness were shown to be significant for predicting the work-to-break of yarn.

Introduction

The tensile properties of HVI bundle are largely determined by the tensile properties of the component fibers within the bundle. Therefore, a proper interpretation and utilization of bundle tenacity-elongation curves require a basic understanding on the relationship between bundle tensile properties and the tensile properties of the fibers making up the bundle. In an effort to increase the utility of HVI tests, "bundle modulus" and "bundle toughness" were estimated from the HVI tenacity-elongation curve. The ultimate objective is to apply them to fiber selection, bale laydown and prediction of spun yarn strengths.

Reprinted from the *Proceedings of the Beltwide Cotton Conference*
Volume 2:1530-1536 (1998)
National Cotton Council, Memphis TN

Experimental Study on Cotton Fiber Properties

For 36 U. S. Upland cottons, the single fiber and bundle were tested by Mantis® and MCI HVI, respectively, from samples taken before carding and after carding. The origins of the 36 cottons are given in Table 1. From each of the thirty six cotton samples, 30/1 Ne carded ring-spun yarns were produced by using a laboratory spinning machine at the USDA-ARS SRRC Lab. The fiber data were compared against the resulting yarn properties in order to examine the relationships among the fiber, bundle and yarn properties.

Mantis® Single Fiber Tensile Properties

A total of 28,800 tests were performed, 400 tests before carding and 400 tests after carding for each of the 36 cotton bales.

Bundle Tenacity-elongation Curves Using Mci Hvi

A total of 216 HVI tests were performed for the 36 U. S. Upland cottons to obtain the bundle tenacity-elongation curves and the micronaire values. For each cotton, 3 beards were tested before and after carding using MCI HVI.

Based on the tests, the effects of carding are shown in Figures 1 ~ 4. It can be seen from the figures that the HVI bundle breaking tenacity, modulus and toughness are shown to be greater after carding while the HVI breaking elongation seems to have been reduced by carding.

In order to gain a better understanding on the relationship among the tensile properties of individual fibers, fiber bundles (HVI beards) and the resulting yarns, the "bundle modulus" and "bundle toughness" were obtained from bundle tanacity-elongation curves. The latter is defined as the total area under the tenacity-elongation curve. The procedures were as follows.

Smoothing Tenacity-Elongation Curves

The actual load during bundle break was estimated by the relationship between the voltage output of the force transducer and the load acting on the transducer. The bundle size was obtained by a direct weighing method. First, the position at which a given beard broke was determined. Then, an 1/8-inch segment of the beard was cut off at the position by use of a special device, and the fibers were weighed on a high precision electronic balance. According to the actual breaking load and actual bundle size, the tenacity (gf/tex) of a bundle was estimated. The actual HVI bundle breaking elongation was obtained by the voltage output of the displacement transducer and the actual displacement. As an example, an HVI bundle tenacity-elongation curve of "DPL 5415" cotton is given in Figure 5 without smoothing.

While an HVI is supposed to measure the load based on a constant rate of elongation, Figure 5 shows that the elongation does not seem to have increased monotonically but rather with many small local oscillations. As this type of noise is quite common in highly sensitive force transducers, and is not easily removed without lowering sensitivity of the instrument, the tenacity and elongation values were smoothed using the Savitzky-Golay [1] method. Seven data points were considered at a time in the smoothing routine. Figure 6 shows the smoothed tenacity-elongation curve of an HVI beard obtained from "DPL 5415" cotton. In combining and comparing more than one tenacity-elongation curves, all curves were shifted and aligned to the one with the smallest elongation. The HVI tenacity-elongation curves obtained before and after shifting are given in Figures 7 and 8. It can be seen that the shape of HVI tenacity-elongation curves are similar within a given cotton.

Estimation of Bundle Modulus from HVI Tenacity-Elongation Curves

The "bundle modulus" was obtained from the bundle tenacity-elongation curve by measuring the rising slope of the load. The slope was obtained by calculating the ratio of two *x*-*y* coordinates from the bundle tenacity-elongation curve, as shown in Figure 9. The (x_1, y_1) is the deflection point on the left portion of the tenacity-elongation curve where the slope begins to stabilize following the removal of fiber crimps and (x_2, y_2) is the point where the slope begins to decrease significantly. Then, the bundle modulus (gf/tex) is computed as $\frac{y_2 - y_1}{x_2 - x_1}$. Figure 9 shows the bundle tenacity-elongation curve with bundle modulus.

Estimation of Bundle Toughness from HVI Tenacity-Elongation Curves

The toughness of a bundle was obtained by numerical integration method using the trapezoidal rule [2]. It represents the entire area under the tenacity-elongation curve, $f(x)$. To evaluate $\int_a^b f(x)\,dx$, the interval from a to b was subdivided into n subintervals, as shown in Figure 10. The area under the curve in each subinterval is approximated by the trapezoid formed by replacing the curve by its secant line drawn between the endpoints of the curve. The integral is then approximated by the sum of all trapezoidal areas. While there is no need to make the subintervals equal in width, the formula becomes simpler by doing so. By letting h be the constant interval width Δx, the area of a trapezoid is obtained by multiplying its average height to the base width of each subinterval as

$$\int_{x_i}^{x_{i+1}} f(x)\,dx \cong \frac{f(x_i) + f(x_{i+1})}{2}(\Delta x) = \frac{h}{2}\left(f_i + f_{i+1}\right)$$

For the entire interval, therefore, the $[a, b]$, n subintervals of size h yield the result

$$\int_a^b f(x)\,dx \cong \sum_{i=1}^{n} \frac{h}{2}\left(f_i + f_{i+1}\right) = \frac{h}{2}\left(f_1 + 2f_2 + 2f_3 + \cdots 2f_n + f_{n+1}\right)$$

Relationship between Single Fiber and Bundle Tensile Properties

The relationship between single fiber and bundle tensile properties was investigated by calculating the correlation coefficients between the fiber and bundle tensile properties.

For the 36 cottons, two sets of correlation analyses were run using the SAS® system in order to evaluate the relationship between the single fiber and bundle tensile properties. The first set provided the correlation coefficients between single fiber and bundle tensile properties from bale. The second set provided the correlation coefficients between single fiber and bundle tensile properties after carding. The correlation coefficients obtained between single fiber and bundle tensile properties were all highly significant (p = 0.0001 ~ 0.0058) as shown in Table 2. Clearly, the single fiber tensile properties have been translated directly into the bundle tensile properties.

It can been seen in Table 2 that the most significant single fiber tensile property which determines the bundle tensile properties is the single fiber breaking elongation. The bundle toughness is shown to increase as the single fiber breaking elongation increases. The bundle modulus is also shown to increase as the single fiber breaking elongation and standard deviation of single fiber breaking elongation decrease. The correlation coefficients are shown to be more significant with the fiber test data taken from card slivers.

Relationships among Single Fiber, Bundle and Yarn Properties

For each of the 36 different 30/1 Ne ring-spun carded yarns produced, the tensile properties were tested 100 times each, 20 times per bobbin for 5 bobbins, using the standard test method. The data were analyzed and compared against the fiber properties.

For the 36 cottons, regression analyses were run using SAS® system in order to evaluate the effects of fiber properties on yarn tenacity. The average for fiber properties and the average yarn tenacity were obtained for each cotton to make up the data points for regression analyses.

For predicting the yarn tenacities of 30/1 Ne ring-spun carded yarns, two sets of multiple regression analyses were run by applying three distinct sets of independent variables; Model I based on HVI and single fiber data (micronaire, strength, S. D. of elongation) from bale and sliver (after carding) samples excluding HVI modulus and Model II by including HVI modulus in place of the S. D. of single fiber breaking elongations. The results are summarized in Tables 3 and 4 and Figures 11 ~ 14.

For predicting work-to-break of the yarn, multiple regression analyses were run by applying the HVI data-. The results are summarized in Table 5 and Figures 15 ~ 16.

The results based on Model I (Table 3 and Figures 11 and 12) show that HVI bundle tenacity and standard deviation of single fiber elongation were the most significant predictor variables ($p < 0.01$). While there have been many reports on the effects of fiber length, micronaire and strength on yarn tensile properties, this study, for the first time, has shown the importance of fiber breaking elongations, especially in terms of their variance.

The results based on Model II (Table 4 and Figures 13 and 14) show that HVI bundle tenacity and bundle modulus are the two most significant predictor variables ($p < 0.01$). The R^2 values remained more or less the same (0.72 vs. 0.74 with "after carding") for Model II when the HVI modulus was used instead of S. D. of single fiber elongation. Here, it is important to note that the HVI bundle modulus is negatively correlated with the standard deviation of single fiber elongation, thus making it an important variable for predicting yarn tenacities. In other words, the bundle modulus obtained directly from HVI tests can be used for predicting the yarn tenacity in lieu of using the standard deviation of single fiber breaking elongation, a measure which is both expensive and time-consuming.

In predicting the work-to-break of the yarns, only HVI bundle breaking tenacity and micronaire are shown to be the significant predictor variables ($p < 0.04$) before carding, whereas HVI toughness and modulus were the significant predictor variables ($p = 0.001$) after carding (Table 5). The predicted and actual works-to-break of yarn are compared in Figures 15 ~ 16. It is clear from the figures that R^2 value improves, i.e., the work-to-break of yarn is predicted better when analyses were run by using the HVI bundle properties measured after carding.

Conclusions

1. A method was developed for estimating the "bundle modulus" and "bundle toughness" of cotton fibers from HVI tenacity-elongation curves in order to gain a better understanding on the relationship between the tensile properties of a bundle and that of its constituent fibers.

2. The single fiber tensile properties were found to be translated well into the bundle tensile properties. The correlations between single fiber and bundle tensile properties become more significant with the data taken after carding.

3. The single fiber breaking elongation and single fiber work-to-break showed highly significant correlations with the corresponding bundle toughness. The single fiber breaking elongation was found to be the most significant contributing factor to bundle tensile properties. The bundle modulus is shown to increase as single fiber breaking elongation and/or standard deviation of single fiber breaking elongation decreases.

4. The HVI bundle tenacity and modulus were found to be significant contributing factors to yarn tenacities.

5. HVI bundle tenacity, bundle modulus, bundle toughness and micronaire were found to be significant contributing factors to work-to-break of the resulting yarns.

References

1. Microcal Origin, Version 3.5, Microcal Software Inc., 1991.

2. Curtis F. Gerald and Patrick O. Wheatley, "Applied Numerical Analysis," 5th Edition, Addison Wesley, PP330 - 335, 1994.

Table 1. Origins of 36 U. S. Upland Cottons Studied.

Cotton Type	Cultivar	Origin
1	DPL 5415	Delta
2	MD 51 ne	MS
3	DPL 4-910-2-2	Delta
4	CA 3084	TX
5	Prema	CA
6	EW 8718-001-101	
7	Maxxa	CA
8	HS 26	TX
9	CAB-CS	TX
10	B 7465	CA
11	SP 93-274	PC
12	DPL 50	Delta
13	TX G3-27	TX
14	STV 474	Delta
15	KC 311	East
16	DPL 5432	AZ
17	Acala 1517-95	NM
18	SP 6-49	PC
19	HQ 95-6	TX
20	GC 95-MS-1	MS
21	SG 501	Delta
22	C-225	CA
23	PD 93057	PD
24	SP 125-401	PC
25	SP 92-219	PC
26	MD 5678 ne	Delta
27	HS 46	MS
28	LA 887	MS
29	El Dorado	CA
30	PD 3-14	PD
31	SP 4-22	PC
32	DPL 0227	MS
33	HX 1220	MS
34	SG 125	Delta
35	Coker 320	East
36	PD 93056	PD

Table 2. Correlation Coefficients between Single Fiber and Bundle Tensile Properties(36 U. S. Upland Cottons).

Single Fiber Tensile Properties vs. Bundle Tensile Properties	Bale		Card Sliver	
	Correlation Coefficients	Prob. > |R|	Correlation Coefficients	Prob. > |R|
Single Fiber Breaking Strength vs. Bundle Breaking Tenacity	0.437	0.0077	0.451	0.0058
Single Fiber Breaking Elongation vs. Bundle Elongation	0.741	0.0001	0.767	0.0001
Single Fiber Modulus vs. Bundle Modulus	0.529	0.0009	0.676	0.0001
Single Fiber Work-to-Break vs. Bundle Toughness	0.634	0.0001	0.800	0.0001
Single Fiber Breaking Elongation vs. Bundle Toughness	0.822	0.0001	0.647	0.0001
Single Fiber Breaking Elongation vs. Bundle Modulus	-0.453	0.0055	-0.713	0.0001
S. D. of Single Fiber Breaking Elongation vs. Bundle Modulus	-0.492	0.0023	-0.719	0.0001

Table 3. Results of Multiple Regression Analyses (Model I).

	Equations	Prob. > |t|	R^2 (*p* value)
Bale	YTS = 5.67 - 1.55 X_2 + 0.53 X_3	X_2: 0.0010 X_3: 0.0001	0.72 (0.0001)
After Carding (Sliver)	YTS = 5.94 - 1.77 X_2^* + 0.49 X_3^*	X_2^*: 0.0012 X_3^*: 0.0001	0.74 (0.0001)

Table 4. Results of Multiple Regression Analyses (Model II).

	Equations	Prob. > |t|	R^2 (*p* value)
Bale	YTS = 1.57 + 0.30 X_3 + 0.09 X_4	X_3:0.0135 X_4:0.0056	0.69 (0.0001)
After Carding (Sliver)	YTS = -2.03 + 0.37 X_3^* + 0.08 X_4^*	X_3^*:0.0003 X_4^*:0.0037	0.72 (0.0001)

Notes: YTS = Yarn Tenacity
X_1 = Micronaire from Bale
X_1^* = Micronaire after Carding
X_2 = S. D. of Single Fiber Elongation from Bale
X_2^* = S. D. of Single Fiber Elongation after Carding
X_3 = HVI Bundle Tenacity from Bale
X_3^* = HVI Bundle Tenacity after Carding
X_4 = HVI Bundle Modulus from Bale
X_4^* = HVI Bundle Modulus after Carding

Table 5. Results of Multiple Regression Analyses for Work-to-Break of Yarn.

	Equations	Prob. > |t|	R^2 (*p* value)
Bale	YW = 0.14 - 0.03 X_1 + 0.01 X_3	X_1:0.0001 X_3:0.0358	0.60 (0.0001)
After Carding (Sliver)	YW = -0.06 + 0.004 X_4^* + 0.008 X_5^*	X_4^*:0.0001 X_5^*:0.0001	0.63 (0.0001)

Notes: YW = Work-to-Break of Yarn
X_1 = Micronaire from Bale
X_3 = HVI Bundle Tenacity from Bale
X_3^* = HVI Bundle Tenacity after Carding
X_4 = HVI Bundle Modulus from Bale
X_4^* = HVI Bundle Modulus after Carding
X_5 = HVI Bundle Toughness from Bale
X_5^* = HVI Bundle Toughness after Carding

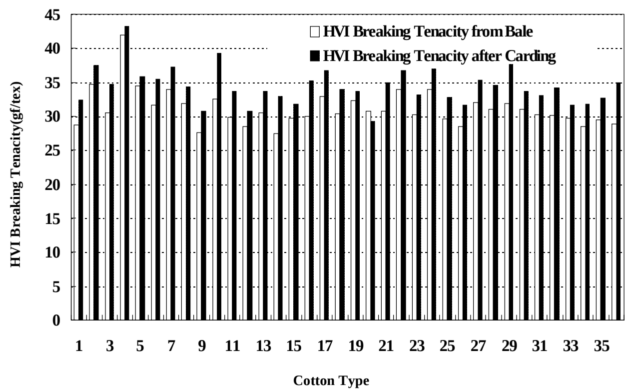

Figure 1. Effects of Carding on HVI Bundle Tenacity.

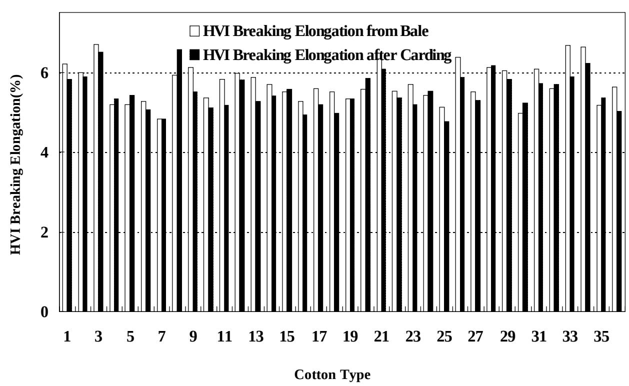

Figure 2. Effects of Carding on HVI Bundle Elongation.

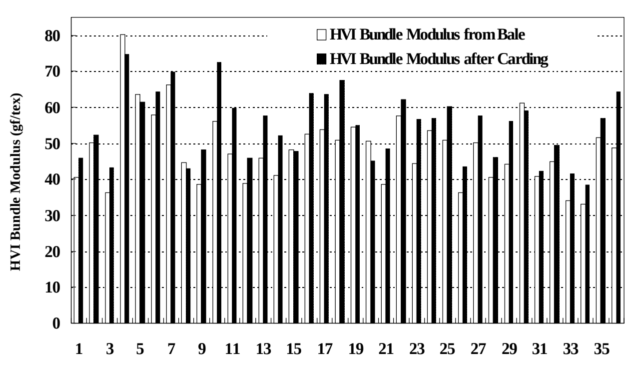

Figure 3. Effects of Carding on HVI Bundle Modulus.

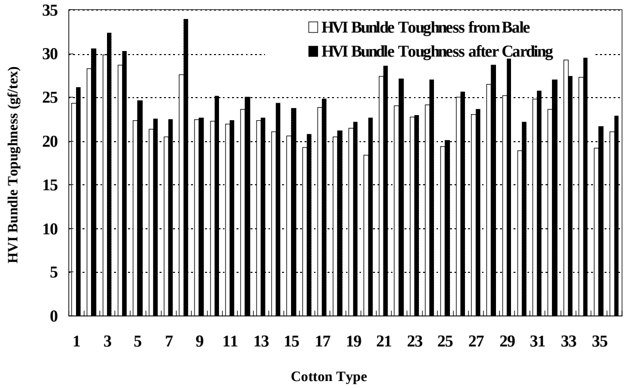

Figure 4. Effects of Carding on HVI Bundle Toughness.

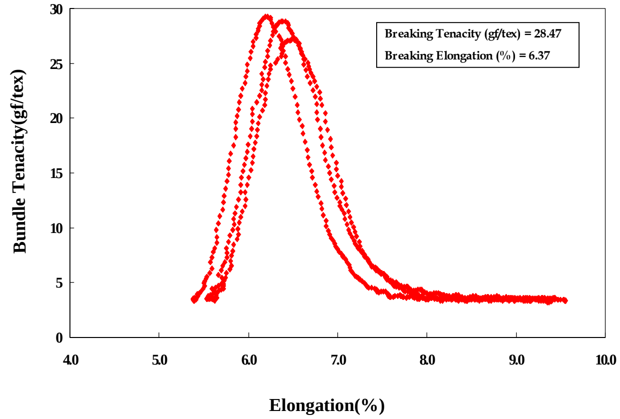

Figure 7. HVI Bundle Tenacity-Elongation Curves before Shifting (DPL5415).

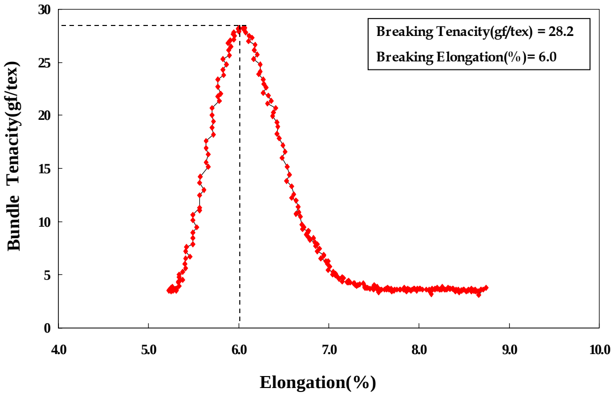

Figure 5. HVI Bundle Tenacity-Elongation Curves before Smoothing (DPL5415).

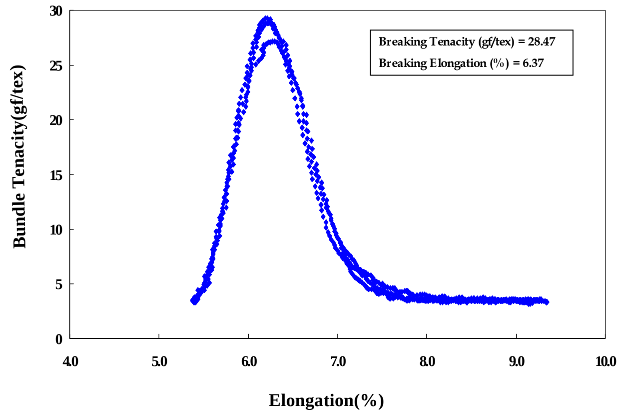

Figure 8. HVI Bundle Tenacity-Elongation Curves after Shifting (DPL5415).

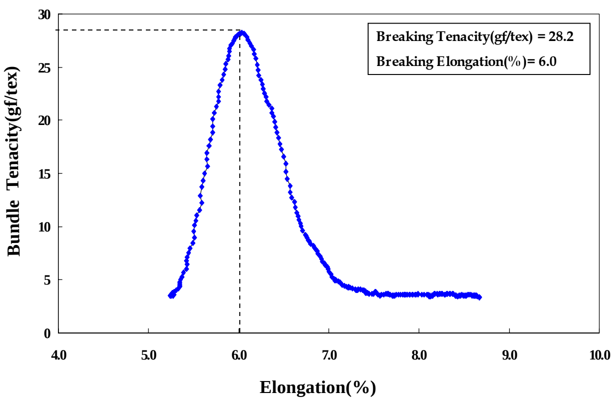

Figure 6. HVI Bundle Tenacity-Elongation Curves after Smoothing (DPL5415).

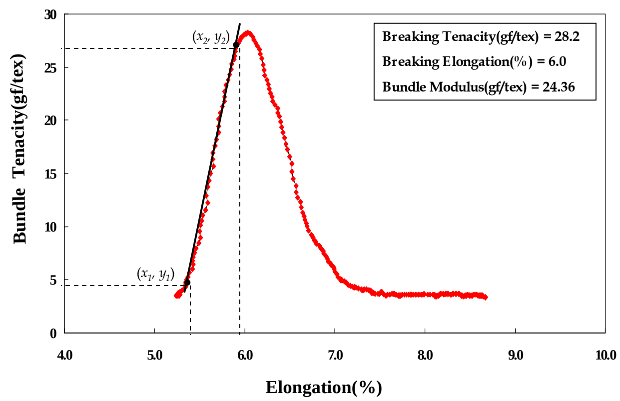

Figure 9. HVI Bundle Modulus (DPL5415).

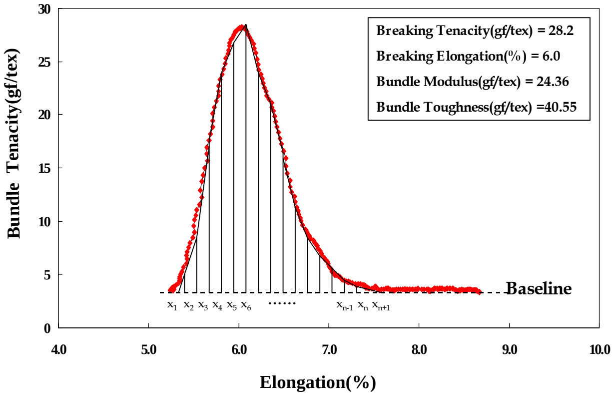

Figure 10. HVI Bundle Toughness (DPL5415).

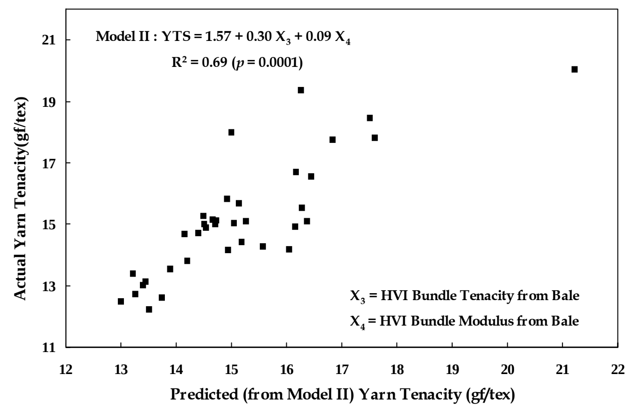

Figure 13. Predicted and Actual Yarn Tenacities - Model II with Bale Data.

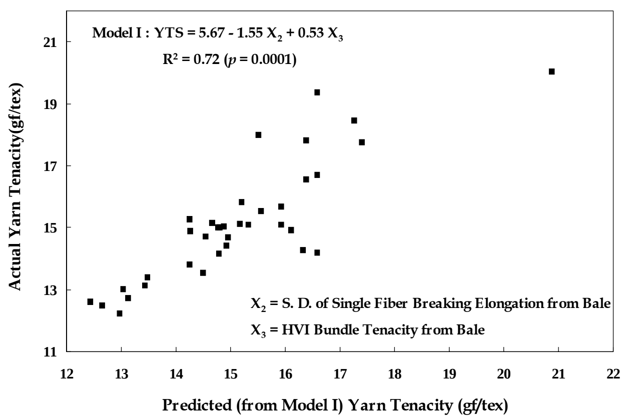

Figure 11. Predicted and Actual Yarn Tenacities - Model I with Bale Data.

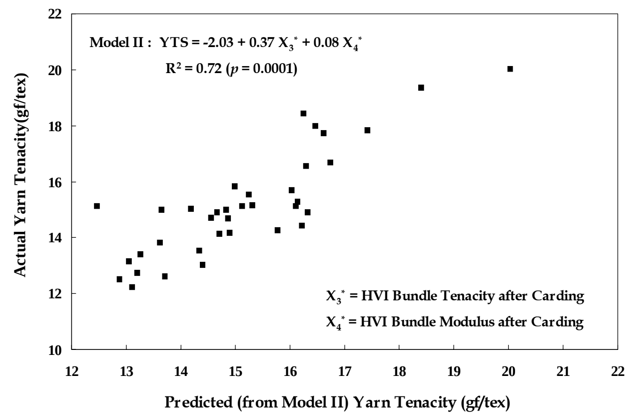

Figure 14. Predicted and Actual Yarn Tenacities - Model II with Sliver Data.

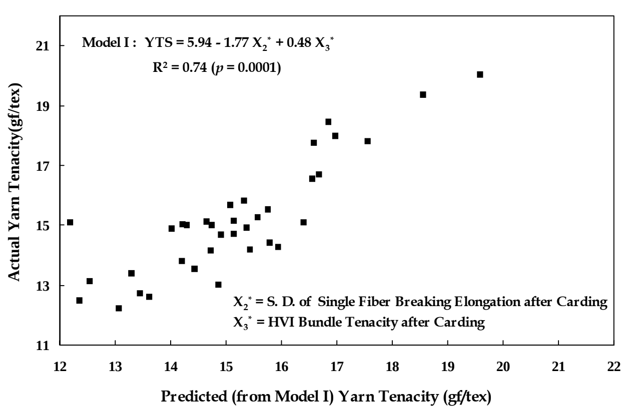

Figure 12. Predicted and Actual Yarn Tenacities - Model I with Sliver Data.

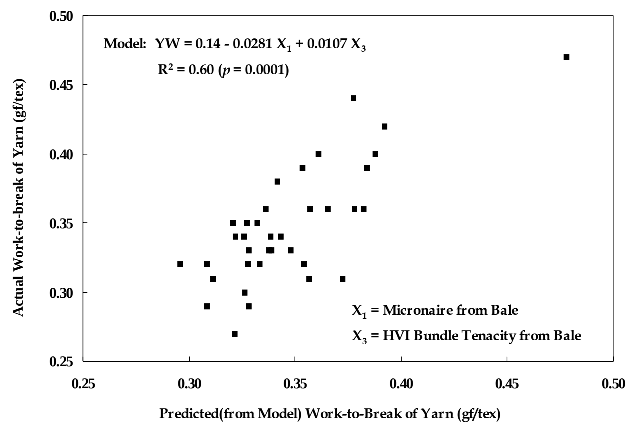

Figure 15. Predicted and Actual Work-to-Break of Yarn - Model with Bale Data.

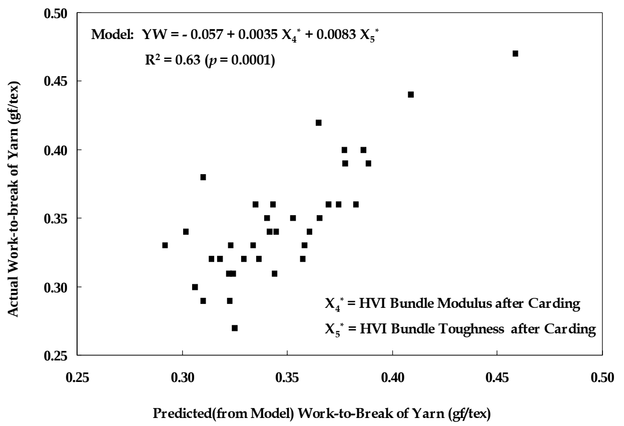

Figure 16. Predicted and Actual Work-to-Break of Yarn - Model with Sliver Data.