COTTON FIBER FRICTION: THE UNKNOWN QUALITY OF COTTON

Yehia El Mogahzy, Roy Broughton Jr. and Hong Guo
Department of Textile Engineering
Auburn University
Auburn, AL
R. A. Taylor
USDA/ARS
Clemson, SC

Abstract

For some who still argue the need for using friction and surface characterization measures of cotton fibers, this paper simply provides evidence of the critical importance of such measures. New techniques are presented, and results covering fiber, yarn, and fabric data are discussed.

Introduction

When one thinks of the basic characteristics that qualify a fiber for conversion into a textile product, flexibility and slenderness are justifiably mentioned as the primary ones. However, as one looks at the way fibers are converted into a yarn or fabric, one can realize that fibers always flow in the process in groups, not as individuals. This is due to the natural clasping power that textile fibers normally exhibit even at minimum external forces.

The technology of converting fibers into yarns was designed in view of the fact that fibers inherently exhibit a significant degree of natural coherence. In fact, a technology that can force fibers to flow individually (for the purpose of perfect control of single fiber flow) is neither possible nor desirable. It is important, therefore, to consider the mutual attraction between fibers as one of the basic characteristics of textile fibers. The general scientific term used for characterizing this attraction is Afriction@ which is defined as the resistance offered to the movement of one body past another body with which it is in contact.

In case of cotton fibers, several factors contribute to the mutual attraction (or friction) between fibers [1]. These include the unique surface morphology with its convoluted or twisted feature (50-100 twists/inch, and C.V% of twist angle is up to 175% within a fiber), the tapered structure (the cotton fiber is tapered at one end and fibrillated on the other end where it is joined to the cotton seed), fiber orientation (natural crimp, and fibrillar arrangement), the capability of taking-up electrostatic charges, and the gross geometrical features (length and fineness). In addition to these factors, the cotton fiber is coated with a natural wax (particularly on the cuticle). This natural wax (basically classed as alcohol or organic solvent extracted materials) acts as a lubricant to smooth and ease the flow of fibers during processing by providing a low resistance to inter-fiber friction. Without this natural lubricant, fiber processing through carding and drafting becomes practically impossible.

These above structural factors contribute collectively and in a very complicated manner to the behavior of fiber flow during processing and to the interaction between fibers in a yarn or fabric under the influence of external loads.

The importance of cotton fiber friction can be best realized when one attempts to rationalize many the common phenomena that occur in practice. These include:

[1] Two cotton mixes both exhibiting the exact same basic fiber properties (e.g. length, strength, and fineness), yet one mix behaves far superior to the other during processing and produces far superior yarn and fabric quality parameters.

[2] Two different types of fibers (say, cotton and polyester) blended together, yet their blend exhibits a value of fiber strength outside the range of the strength values of the individual components of the blend.

[3] A yarn made from certain fibers exhibit a tenacity far inferior to the respective fiber tenacity (low fiber/yarn strength efficiency).

[4] Chaotic swings in fabric tear resistance.

[5] Excessive sliver breaks during drafting and roving and excessive consequent spinning endsdown.

[6] Difficult or near-impossible processability of scoured and bleached cottons.

[7] The cluster of fibers exhibiting unfavorable characteristics during processing or in the yarn structure [e.g. short/course fibers, sticky fibers, immature fibers, etc.].

[8] The sensitivity of fiber processing performance to external conditions [mechanical or environmental].

[9] The complex phenomena of comfort and hand of different fabrics.

[10] Some fibers require higher optimum twist than others despite the similarity in basic fiber characteristics .

[11] Static charges and liberation of short fibers, lint fly, and dust during processing.

All of the above phenomena are associated, at least in part, to the frictional behavior of cotton fibers. Therefore, any rationalization or attempt to govern these phenomena should be based on understanding the role of cotton

Reprinted from the *Proceedings of the Beltwide Cotton Conference*
Volume 1:545-552 (1997)
National Cotton Council, Memphis TN

friction. This understanding requires the availability of reliable methods for characterizing the morphology of cotton fiber surface, and for measuring inter-fiber and fiber/solid friction.

In this paper, we will briefly discuss some of the new methods developed in Auburn University laboratory for measuring fiber friction and some of the interesting results obtained from these methods. For more detailed analysis of the subject, the reader is encouraged to refer to the previous papers published by the present authors and by other distinguished scientists [Ref. 1-9]. The reader may also contact the principal author (Dr. El Mogahzy at (334)844-5463, or E-mail: yehiae@eng.auburn.edu.

Friction Measurement: Basic Criteria

The basic principle of any friction measurement should involve sliding of two surfaces against each other and measuring the resistance to sliding under a certain level of normal load. Traditionally, three different types of friction measurement have been utilized for fiber assemblies. These are the point contact method, the line contact method, and the area contact method. Basic principles associated with these methods are illustrated in Figure 1. As a result of the obvious differences in surface configuration between these methods, they involve different sample preparation techniques, and different analytical approaches. In general, dealing with point or line contact method involves specimens of single fibers or yarns. Accordingly, these two methods require careful preparation of specimens; more importantly, several tests are needed for statistical reliability. The area contact method, on the other hand, requires less number of tests for a given sample, but careful sample preparation remains important.

Any friction testing technique should be evaluated based on the following criteria:

(1) The method of sample preparation.
(2) Types of friction parameters, measured or derived.
(3) Reproducibility and reliability of friction data.
(4) The time required to perform the test.
(5) The capability of the technique to simulate the desirable friction process.

Among the above criteria, the fifth one deserves a special attention. It is critical that the friction method used should simulate the purpose for which friction measurements are taken. The three contacting modes illustrated in Figure 1 represent the basic forms of fiber contact that can be witnessed in practice. The point contact may closely resemble single fibers crossing one another in a disoriented or random fiber web; it may also resemble, with some approximation, the rubbing action between crossed yarns (fillings and warps) during weaving or the looping format during knitting. The line contact may resemble the rubbing action between fibers during drafting; it may also resemble the friction between parallel yarns in the warp direction during weaving. The area contact is commonly witnessed in situations where aggregates of fibers slide against one another during carding or drafting, or when fabric sheets are being pulled over guide rolls.

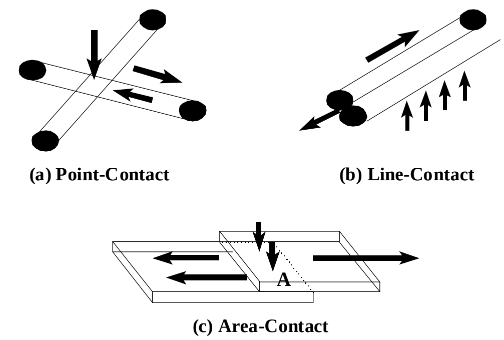

Figure 1. Methods of Friction Measurement.

In addition to the above basic modes of contact, more complex modes of fiber interaction may be found in practice. One of the most familiar modes is that of fibers being sheared in the carding zone. Figure 2 illustrates this mode and the various stresses applied on the fiber aggregates in this critical zone [11,12]. As can be seen in this Figure, fibers are interacting with one another, adhering around the main cylinder wires, and being caught by the top flats. In addition, they are flowing against an air drag created by the narrow carding zone. This multiple contact mode is a result of the various forces applied on the fibers in the carding zone. These forces include:

a. The centrifugal force against the fiber flock on the carding cylinder [see Figure 2.a]. This force is a function of the mass of the fiber flock, m, the radius of the cylinder, R, and the square of the cylinder speed, T5. At high speed carding, the fiber flock will have a tendency to fly away from the cylinder clothing toward the slowly rotating flats. This results in more adherence between the fibers and the flat surface.

b. Friction forces between the fiber flock and the cylinder cloth wire [see Figure 2.b]. These forces are generated by the lateral pressure between the fiber flock and the wire surface. This pressure is a result of the compacting effect of the fiber volume supported by the wire configuration. The higher the carding rate, the higher the lateral pressure, and the higher the corresponding generated friction stresses.

c. The air friction force (drag) which is a result of the narrow slot between the cylinder and the flats. Because of the difference between cylinder and flats speeds, the air friction force is expected to result in a relative displacement between different fiber layers in the flock with fibers on the cylinder surface exhibiting higher speeds than those closer to the flats (i.e. friction between fiber layers). The air friction force will depend on the shape of the flock, the air viscosity, the air speed, and the flock density.

d. The opening force [see Figure 2.c]. This force represents the actual carding force which depends on the level of compactness of the entering flock. Accordingly, a fiber compression force F_c will exist which depends on the fiber mass for a given setting. Since the flat and cylinder continue to rotate with greatly different speeds, attachment of fibers to both clothings will result in an opening force, F_{op}. This force is greatest at the first flat and it gradually decreases as the opening process continues. The opening force is, therefore, dependent on the fiber orientation within the flock.

The complex contact mode illustrated in Figure 2 can not be resembled by one of the modes illustrated in Figure 1. In other words, a testing technique that can characterize the frictional behavior during carding can only be achieved through a complete simulation of the carding action.

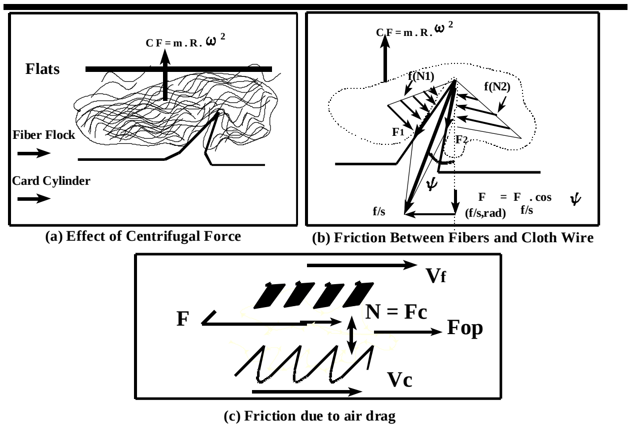

Figure 2.

Friction Testing Techniques

In recent years, several techniques have been developed for characterizing the frictional behavior of staple fibers. Table 1 provides a summary of some of the techniques and their associated criteria. In the following sections, we will discuss some of the more recent development in friction testing techniques.

Table 1. Different Friction Testing Techniques Used for Measuring Friction of Staple Fibers

Test Method	Sample Form	Friction Mode
Sled Test	Fiber Web	Fiber/fiber
Auburn-Beard Test	Fiber Beard [e.g. HVI Beard]	Fiber/fiber & fiber/metal
Rotor Ring	Raw fibers or sliver	Fiber/metal
Modified Rotor Ring	Raw fibers or sliver	Fiber/fiber & fiber/metal
Cohesion Test	Sliver	Sliver strength

Table 1 continued.

Test Method	Applications	Testing Time [per single test]
Sled Test	- Surface Treatments - Nonwovens	25 minutes
Auburn-Beard Test	- Surface Treatments - Nonwovens - Fiber/Yarn Modeling	3 minutes
Rotor Ring	- Processibility Index	2-4 minutes
Modified Rotor Ring	- Processibility Index	2-4 minutes
Cohesion Test	- Drafting Performance	Depends on sliver preparation time

The Auburn-Beard Test: Basic Friction Measurement

In a previous study [1,2, 3], we developed the so-called Auburn-Beard Test [see Figure 3] which represents a case of area-contact through the use of a flat beard of cotton fibers. In recent months, this method has been developed further to ensure a direct measurement of fiber-to-fiber friction. Features of the new Auburn-Beard Test include a new driving system with a smart motor, direct computer integration, and a patented inter-fiber contact mode. Figure 4 shows a schematic of the new development. Evaluation of this system is being made and the results will be published soon.

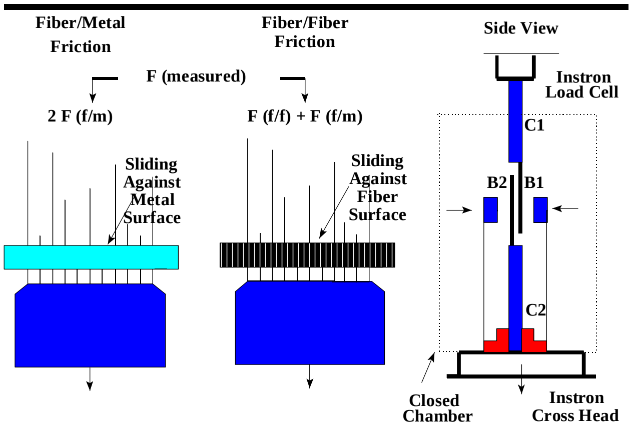

Figure 3. Auburn Beard Friction Test.

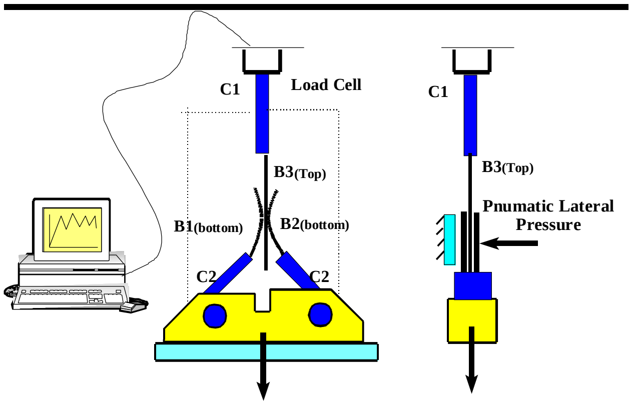

Figure 4. The New Auburn Beard Friction Test.

The Conventional Rotor-Ring

The conventional rotor-ring basically consists of a rotor spinning unit. As shown in Figure 5, the rotor ring consists of feed chute, housed feed roller, an opening roller, a rotor feed, and a rotor. This device was developed by the Institute for Textile Technology, Reutlingen, Germany, and it has been commercially distributed by Zellweger Uster. The fibers are fed by hand into the feeding unit. The feeding roll transports the fiber tufts, at low speed, to the opening roller which rotates at high speeds (3000-6000 rpm). The opening roll opens the fiber tufts down to smaller fiber aggregates. The fibers are then sucked off the opening roller and fed into the rotor. Under the centrifugal force created by the high rotor speed (8000-12000 rpm), fibers are condensed onto the rotor wall. This results in the formation of a ring of parallel fibers. Thus, a ring of fiber sliver is produced and is then removed from the rotor when it is stopped.

The primary reason for the development of the rotor ring was to use it as tool to prepare a uniform sliver from a small amount of raw fibers (about 2 g) and in a short period of time (typically less than one minute). Other applications such as blending of various components of fibers, and measurement of crimp and friction came as potential uses of the rotor ring that have to be evaluated by individual users.

The concept of using the conventional rotor ring for measuring fiber friction was initially based on the idea that the actual width of the fiber ring formed depends on several interactive factors including fiber crimp, fiber-to-fiber friction, fiber-to-metal friction, and bending modulus. Thus, fiber interaction can be indirectly measured through the measurement of the width of fiber ring. Furthermore, one can take the prepared sliver and measure its cohesion using a sliver cohesion tester or a standard tensile test.

In a later development, the rotor ring itself was used as a testing instrument of fiber friction. This was achieved through measuring the energy required to open the fibers in the rotor ring. In this regard, the power needed to drive the opening roller is measured.

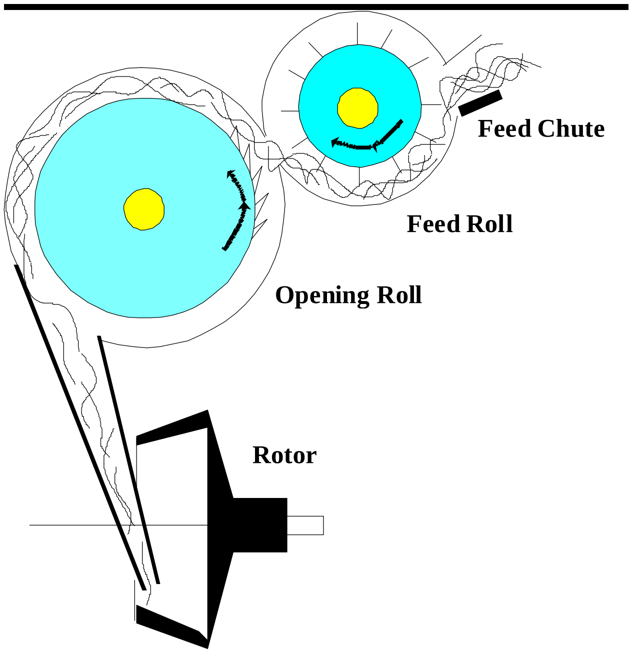

Figure 5. The Conventional Rotor-Ring.

Evaluation of the Conventional Rotor Ring

As a part of our research activities, we evaluated the rotor-ring capability of characterizing fiber friction. The results of this evaluation are summarized in Figures 6 and 7.

As can be seen in Figure 6, the increase in sample weight resulted in an increase of both the power reading and the fiber ring width. These results indicate that the rotor-ring is responsive to the rate of throughput in a way that is largely resembling an opening unit in the textile operation. As the amount of input material per unit time increases, the energy required to open the material will increase.

The results in Figure 7 indicate that as the opening roll speed increases, the power reading increases, and the fiber ring width decreases. The increase in power reading with the opening roll speed is expected on the basis that the power required to drive the opening roll is a direct function of the opening roll speed. However, the significant difference in power reading between the first run and the other two runs indicates that the increase in power with opening roll speed will also depend on the input material orientation (being the worst in the first run). The reduction in the fiber ring width with the increase in opening roll speed is a result of better separation of fibers and a consequent improvement in fiber compactness in the rotor.

Our purpose of using the rotor ring was to discover whether it has potentials beyond its known capability of preparing a sliver. The above discussion clearly reveals that the rotor ring closely resembles an opening unit in both its components and in the way it responds to both material throughput and changes in opening speed. The fact that we can measure the power needed for driving the opening roll during processing of certain material clearly indicates that we may be able to use the rotor ring as a useful tool for testing fiber Aprocessability@.

When one speaks of a certain parameter to be tested, one normally has a well established understanding of the physical meaning of the parameter. Ironically, the term Aprocessability@, as often as it is being used, is not fully understood. Yet, every body in the field knows it when fibers exhibit good or poor processibility.

In general, we may attempt to define processibility as Athe ease of fiber flow during processing@. This ease is often a result of a combination of many parameters including inter-fiber friction, fiber-to-metal friction, and air drag. The power reading produced by the conventional rotor-ring essentially implies this complex combination without indication of the relative importance of any of these parameters. In this regard, the most critical zone of the conventional rotor ring is that between the opening roller and the feeding roller. In this zone, the fibers are being opened while momentarily gripped by the feeding roll and then transferred to the opening roll. This arrangement places more emphasis on fiber-to-metal friction over the other two parameters.

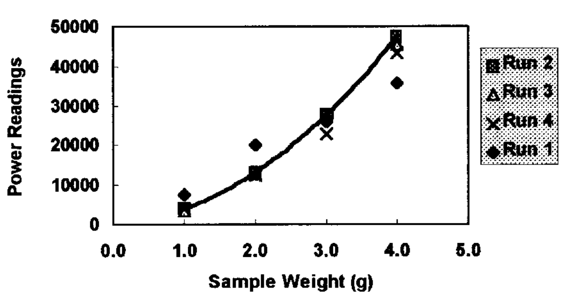

Figure 6a. Power Reading at Different Sample Weight [Opening Roll Speed = 5000 rpm, Rotor Speed = 10000 rpm, Time = 39 secs, Cotton (4.5 Mic, 1.0 inch FL)].

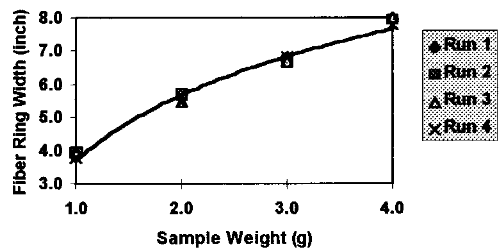

Figure 6b. Fiber Ring Width at Different Sample Weight [Opening Roll Speed = 5000 rpm, Rotor Speed = 10000 rpm, Time = 39 secs, Cotton (4.5 Mic, 1.0 inch FL)].

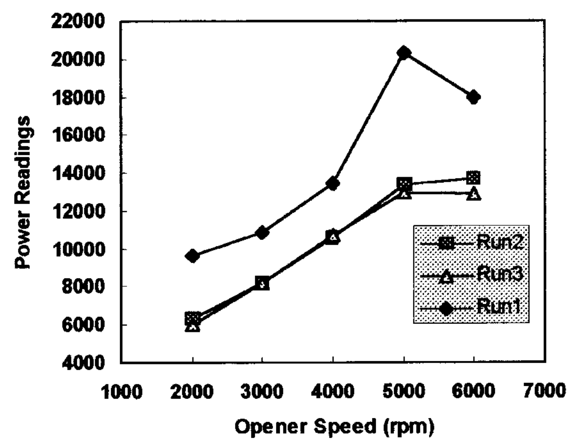

Figure 7a. Power Reading at Different Opening Roll Speed [Rotor Speed = 10000 rpm, Feed Speed = 5 rpm, Weight = 2g, Time 39 secs, Cotton (4.5 Mic, 1.0 FL)].

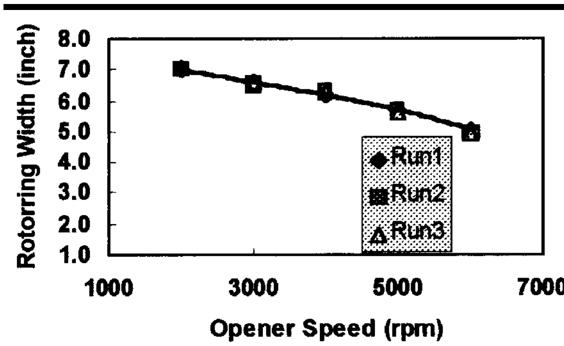

Figure 7b. Fiber Ring Width at Different Opening Roll Speed [Rotor Speed = 10000 rpm, Feed Speed = 5 rpm, Sample Weight = 2g, Time 39 secs, Cotton (4.5 Mic, 1.0 FL)].

<u>The Modified Rotor-Ring</u>

In an attempt to reveal some of the potentials of the rotor ring, we made a slight modification to the conventional arrangement by mounting a sand paper in the inside wall of the top casing of the opening roll. The purpose of this modification was to simulate a carding action with the sand paper being a resemblance of a carding segment [see Figure

8]. As a result of this arrangement, fibers transferred to the opening roll were momentarily caught by the carding segment, and a shearing action or fiber-to-fiber friction was accomplished. The effect of this modification was evident from the extensive testing made and the numerous results obtained.

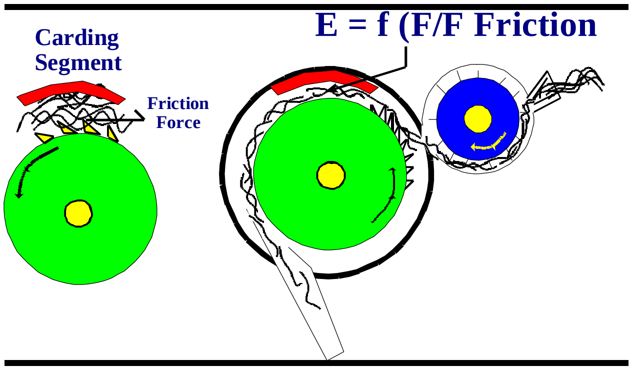

Figure 8. The Modified Rotor-Ring.

Results and Discussion

In this section, we will discuss some of the interesting results that we obtained using the modified rotor ring. The data used represent 34 different cotton bales produced 1993 and 1994. These cottons were collected from different areas including the Southeast, Texas, and California. Some of these bales were processed into 6's rotor spun yarns. The yarns were then woven as filling in denim fabric. The same warp material and weave construction was used to prepare all fabric samples.

A series of fiber, yarn, and fabric tests were conducted at the USDA Clemson laboratory. Rotor ring tests and sliver cohesion tests were performed at Auburn Textile Department laboratory. In addition, measurements of Wax percent were conducted by Bob Taylor using Near-infrared reflectance [13]. Summary of the results of different tests are shown in Tables 2 and 3.

Significant Correlations Between Friction Parameters and other Fiber Attributes

Table 4 shows some of the significant correlations between friction parameters and other fiber attributes. As can be seen in this Table, there is an inverse correlation of -0.554 between the NIR wax content and the modified rotor ring power reading (MRR-power). This degree of correlation is considerably high in view of the fact that the cotton bales also exhibit different values of fiber attributes (e.g. length, fineness, and maturity). The relationship between MRR-power reading and the NIR wax content is also shown in Figure 9. The power reading of the conventional rotor ring (RR-power) also provided an inverse relationship with NIR

Table 2. Summary of Fiber Quality Measurements

Fiber Quality	Mean	Min	Max
HVI (MCI 3500) Strength (g/tex) Length (inch) Uniformity Micronaire Color (Rd) Color (+b)	 27.9 1.08 81.4 4.3 72.5 8.98	 25.3 1.01 79.4 3.2 62.1 6.5	 33.9 1.13 84.9 4.9 81.7 12.8
Micromat Maturity (%) Maturity Ratio	 80.2 0.90	 63.7 0.71	 88.0 1.00
NIR: Wax Content (%)	 1.44	 0.98	 2.23
Rotor-Ring Energy Index: Conventional Modified	 33816 38189	 28866 33334	 39415 43977
Sliver Cohesion (lb):	0.096 3	0.067 8	0.1196

Table 3. Summary of Yarn and Fabric Measurements

Yarn Quality	Mean	Min.	Max.
Tenacity(g/tex)	14.0	11.97	16.4
Yarn Elongation (%)	6.7	6.07	8.01
Skein Break Factor CSP (lb. Ne)	2394	2022	2824
Fabric Tear Strength (lb)	11.6	9.4	14.6
Fabric Tensile Strength (lb)	163	149	178

wax content but at a lower degree of correlation (r= -0.392).

As a further confirmation of the above results, values of rotor ring power reading were plotted against NIR wax content for bales exhibiting extreme levels of wax content. Figure 10 shows these plots for both the conventional and the modified rotor ring. One can clearly see the superior results associated with the modified rotor ring over those of the conventional one.

Table 4 also shows that there is a moderate negative correlation between sliver cohesion and NIR wax content, and a moderate positive correlation between sliver cohesion and MRR-power reading. These correlations are physically expected.

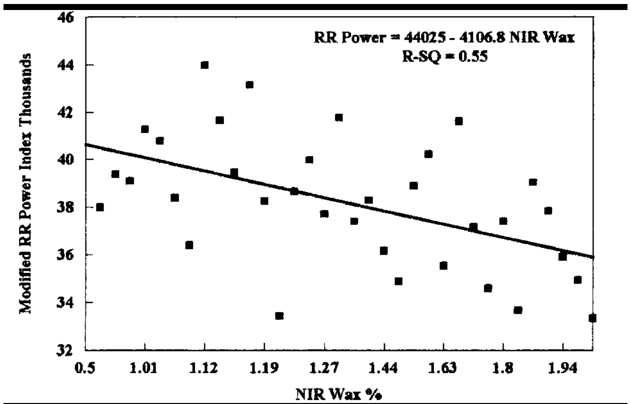

Figure 9. Relationship Between the Power Reading of the Modified Rotor Ring and NIR Wax Content.

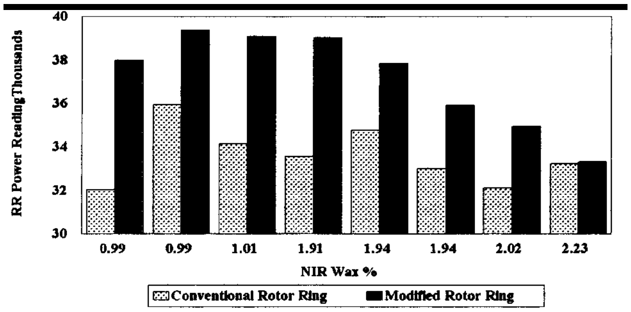

Figure 10. Rotor Ring Power Readings at Extreme Values of NIR Wax %.

With regard to other fiber attributes, the results of Table 4 reveal several interesting correlations. The first one is a significant negative correlation between the NIR wax% and Micronaire or maturity ratio. This negative correlation may be attributed to the fact that NIR wax measurements were taken over a constant sample surface (12 square inch) which may contained more fine fibers than coarse fibers.

The second interesting correlation is that between NIR wax content and cotton color (Rd and +b). As can be seen in Table 4, both Rd and +b exhibited significant positive correlations with NIR wax content. Figures 11 and 12 show these relationships, and Figure 13 shows the values of NIR wax content at different Rd/+b combinations for cotton samples exhibiting equal Micronaire and maturity ratio values. The validity of these correlations is further confirmed by the negative correlations between these two color parameters and both the MRR-power reading and sliver cohesion. We will not attempt to provide a physical explanation to the increase in wax content with both Rd and +b, but we hope that further analysis of these interesting correlations can be made in the near future.

Table 4. Significant Correlation Coefficients Between Friction Parameters and Other Fiber Attributes

	NIR Wax%	RR-Power	MRR-Power	Sliver Cohesion
NIR Wax%	1.00	-0.385	-0.554	-0.392
RR-Power		1.00	0.530	NS
MRR-Power			1.00	0.300
Sliver Cohesion				1.00
Micronaire	-0.570	NS	0.265	0.360
UHML	NS	NS	NS	0.320
Color Rd	0.462	NS	-0.250	-0.320
Color +b	0.470	-0.300	-0.400	-0.254
Maturity Ratio	-0.518	0.210	0.314	0.205

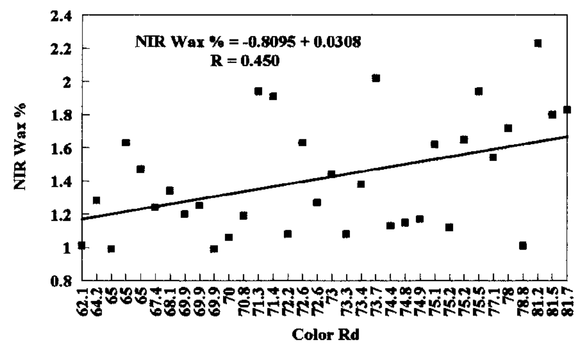

Figure 11. Relationship Between NIR Wax Content and Color Reflectance Rd.

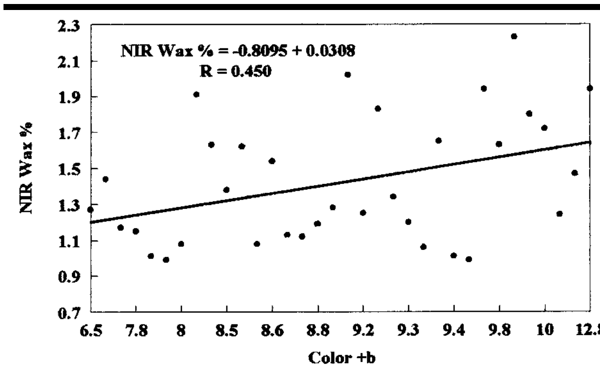

Figure 12. Relationship Between NIR Wax Content and Color +b.

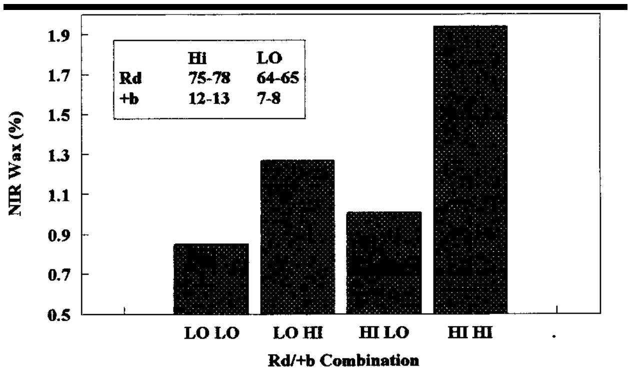

Figure 13. NIR Wax Content at Different Rd/+b Combinations [All Samples of Equal Micronaire = 4.5, Equal Maturity Ratio = 0.9].

Effects of Frictional Parameters on Yarn and Fabric Characteristics

Table 5 shows correlation coefficients between friction parameters and some yarn and fabric properties. As can be seen in this Table, NIR wax content has high positive correlations with yarn and fabric strength. MRR-power reading and sliver cohesion exhibited negative correlations with these two parameters. These correlations may be explained on the ground that smooth processibility (high wax content and low rotor ring power) provides an environment in which fibers can contribute effectively to the strength of yarns and fabrics. From a more physical viewpoint, yarns made from low friction fibers should produce fabrics of high tear strength due to the enhancement of fabric assistance during tearing.

Table 5. Correlation Coefficients Between Friction Parameters and Yarn & Fabric Attributes.

	NIR Wax %	MRR-Power	Sliver Cohesion
Skein Yarn Strength (CSP)	0.629	-0.260	-0.200
Single Yarn Strength	0.569	-0.258	-0.221
Yarn Elongation	NS	-0.180	-0.220
Fabric Tensile Strength	0.478	-0.243	-0.180
Fabric Tear Strength	0.576	-0.300	-0.210

The effects of friction parameters on yarn and fabric properties were also illustrated using two bales exhibiting approximately the same standard fiber properties (strength, length, and fineness) but different in their frictional characteristics. Figures 14 through 17 show those effects. These results clearly indicate the critical importance of measuring friction parameters. The availability of such measures will certainly explain some of the chaotic changes that we often see in yarn or fabric properties even when standard fiber measures are within acceptable ranges.

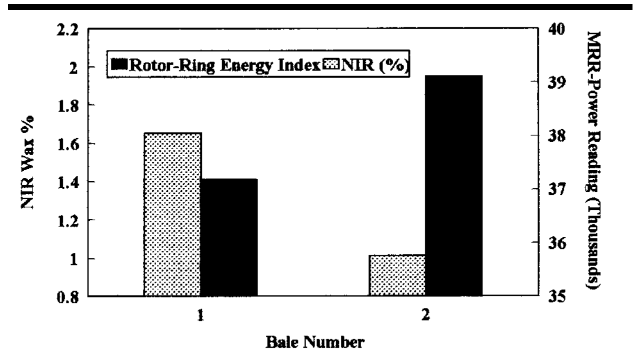

Figure 14. Values of NIR Wax % and Rotor-Ring Energy for Two Different Cotton Bales each of Mic = 4.5, FS = 26.5 g/tex & UHML = 1.07.

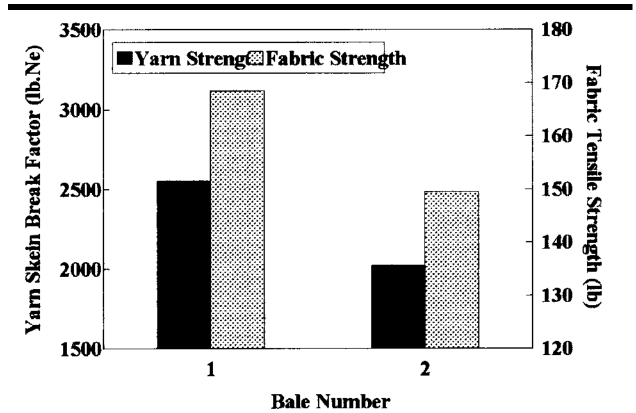

Figure 15. Values of Yarn Strength and Fabric Tensile Strength Mic = 4.5, FS = 26.5 g/tex, UHML = 1.07

Figure 15. Values of Yarn Strength and Fabric Tensile Strength.
Mic = 4.5, FS = 26.5 g/tex, UHML = 1.07.

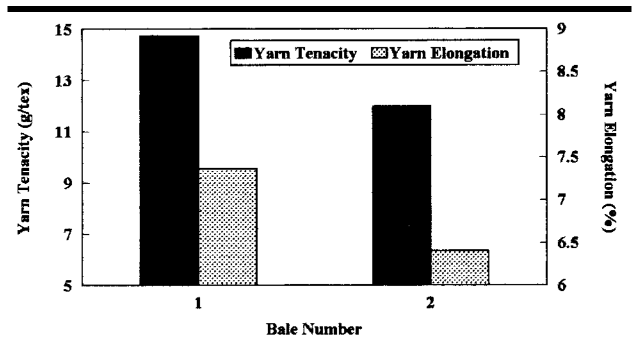

Figure 16. Values of Single Yarn Tenacity & Yarn Elongation for Bales 1 & 2 [Mic = 4.5, FS = 26.5 g/tex, UHML = 1.07, Ne = 6's-Denim Yarn].

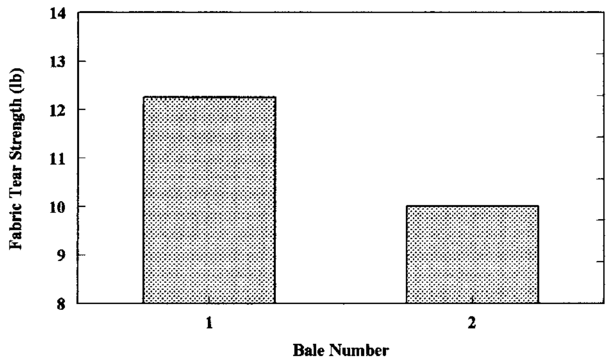

Figure 17. Values of Fabric Tear Strength for Bales 1 & 2 [Mic = 4.5, FS = 26.5 g/tex, UHML = 1.07, Ne = 6's-Denim Yarn].

References

El Mogahzy, Y. E., Broughton, R., and Wang, Q., The Frictional Profile of Cotton Fibers and its Importance in Determining Fiber Performance in the Nonwoven Process. Part I: Fundamental Aspects of Fiber Friction and Lubrication. International Nonwovens Journal, Vol. 7, No. 1, pp 26-33, 1995.

El Mogahzy, Y. E., Broughton, R., and Wang, Q., The Frictional Profile of Cotton Fibers and its Importance in Determining Fiber Performance in the Nonwoven Process. Part II: Experimental Observations. International Nonwovens Journal, Vol. 6, No. 4, pp 35-42, 1994.

El Mogahzy, Y., and Broughton, R., Jr., A New Approach for Evaluating the Frictional Behavior of Cotton Fibers. Part I: Fundamental Aspects and Measuring Techniques. Textile Res. J. Vol. 63, No. 8, pp 465-475, 1993.

Lord, E., Frictional Forces Between Fringes of Fibers, Journal of the Textile Institute, Vol. 46, P 41-58, 1955.

Viswanathan, A., Some Experiments on the Friction of Cotton Fibers, J. Tex. Inst., No. 10,64, pp 553-557, 1973.

Viswanathan, A., Frictional Forces in Cotton and Regenerated Cellulosic Fibers, Journal of the Textile Institute, Vol. 57, No. 1, pp T30-T40. 1966.

Duckett, K. E., Surface Properties of Cotton Fibers, Fiber Science Series, Surface Characteristics of Fibers and Textiles, M.J. Schick Editor, Part I, Marcel dekker, Inc. NY and Basel, 1975.

El Mogahzy, Y. E., A Study of the Nature of Friction in Fibrous Materials, Ph.D Dissertation, N.C. State University, Raleigh, NC. 1987.

Wang, Q., A Study of the Nature of Cotton Fiber Friction, A MS dissertation, Auburn University, 1994.

ASTM 1894-78 Standard Test Method for Static and Kinetic Friction of Plastic Film Sheeting.

Artzt, P., and Schreiber, O., Determination and Parameters of the Carding Forces of High Speed Cards at Production Rates above 30 kg/hr, Melliand Textilberichte International, ED, Volume 3, No. 4, pp 224-230, 1974.

Belogolovtsev, S. D., and Surkova, T. A., The Length of the Doffing Arc on the Card, Tech. of Textile Industry, U.S.S.R., No. 5, pp 33-38, 1971.

Taylor, R. A., Measuring Natural Waxes on Cotton Using NIR Absorbance. Proceedings of the Beltwide Cotton Conference, Publications of the National Cotton Council, January 1997.