

TEXTILE TECHNOLOGY

The Influence of Surface Electrolyte and Moisture Content on the Frictional Behavior of Cotton Fiber

Gary R. Gamble

ABSTRACT

Cotton processing efficiency is dependent on the degree of friction between fibers and their processing environment as the fibers are subjected to the various pieces of equipment involved in converting fiber to yarn. This frictional behavior is a function of both fiber morphology and fiber surface characteristics. In this study, fiber surface electrolyte content and the moisture associated with the fiber were investigated to determine their potential role in the conversion of fiber to yarn. A single cultivar of cotton grown in Georgia during the 2003 crop year was treated with different electrolyte solutions at various concentrations, and then the frictional behavior of the cottons was examined using the Rotorring measurement. Results indicated that a coating of electrolyte on the surface of the cotton fiber may lead to either an increase or a decrease in fiber friction. The more hygroscopic electrolytes in general were responsible for increases in fiber-to-metal friction. Fiber-to-fiber friction was increased by all surface electrolyte treatments, which lead to the conclusion that the electrolyte content in conjunction with surface moisture confers anti-electrostatic properties that increases the coherence between individual fibers. Knowledge of this property will aid in predicting the processing performance of cotton fiber and the possibility of adjusting that performance through the application of electrolyte solutions to the fiber.

It is widely recognized that the processing behavior of cotton fiber is governed to a considerable extent by the degree of coherence between the fibers in a bulk sample. Without this natural coherence, it would not be possible to form a useful yarn from a group of individual fibers. Previous work has demonstrated that different cottons do not necessarily possess the

same degree of fiber cohesion, and that differences in cohesion are correlated with differences in processing efficiency (Graham and Bragg, 1972; McAlister et al., 2003). Traditional textile processing includes a series of drafting processes which are dominated by the interaction between groups of fibers. It has been shown that traditionally measured fiber properties, including length, strength, and fineness, do not fully account for the observed differences in processing performance or resulting yarn quality (El Mogahzy and Robert, 1992). Other fiber features, including fiber convolution, fiber reversals, surface finish, and electrostatic potential, have been suggested as possible contributors to inter-fiber friction (El Mogahzy et al., 1995). Several methods, including the sliding of one fiber fringe over another under an applied load (Lord, 1955), a draft zone simulation measurement on roving prepared for ring spinning (Graham and Bragg, 1972), and the cohesion test (ASTM, 1997), have been developed to measure inter-fiber friction. In addition to inter-fiber friction, there are also interactions between fibers and processing equipment at each stage of yarn production. This is especially true in rotor spinning and air-jet spinning, where the fibers experience a higher degree of surface contact with processing equipment and move at faster rates. Several instrumental techniques, including the Auburn Beard test (El Mogahzy and Broughton, 1993) and the Rotorring (Ghosh et al., 1992), have been utilized to simulate the frictional forces between cotton fibers and their processing environment.

The Rotorring was initially developed as a method to quickly form a uniform sliver in a short period of time from a small quantity (2 to 3 g) of raw fiber. In later development, this instrument was used to measure the fiber cohesion characteristics of man-made fibers (Ghosh et al., 1992). Fiber cohesion was influenced by a number of variables, such as fiber length, fiber finish, crimp, and surface roughness. In addition, cohesion may also be influenced by factors, such as the cross-sectional shape of the fiber. In these tests, both the energy required to open the fibers and the width of the resultant sliver were measures of fiber cohesion. The development of the Rotorring as

a technique to measure the frictional forces of cotton fibers came later (El Mogahzy et al., 1997), and it has been demonstrated that this technique provides a useful method to realistically simulate the forces encountered by cotton fibers during processing.

The Five Year Leading Varieties Study being conducted at USDA-ARS Cotton Quality Research Station includes the measurement of fiber friction using the Rotorring, as well as quantification of chemical factors on fibers, including wax, pectin, soluble electrolytes, moisture, and sugars. Results have indicated that the force necessary to open a single fiber from a 3-g sliver is correlated with bulk moisture content, pectin content, sugar content, and electrolyte content (Gamble, 2004). Wax content, however, was shown to exert little or no influence on fiber frictional measurements when present at naturally occurring levels, although it has been demonstrated that complete removal of the surface wax layer from cotton has a dramatic effect on friction (Cui et al., 2002). Those chemical factors correlated with fiber friction were further shown to be collinear, implying that any combination of these chemical factors is potentially related to the observed frictional behavior.

The objective of this study was to independently examine the effects of surface moisture and electrolyte content on cotton fiber friction as measured by the Rotorring. This was achieved through the use of fiber sample from a single cotton cultivar grown in one location during the 2003 crop year. The sample was thoroughly washed in order to remove all soluble components, primarily sugars and salts, and subsequently treated with different concentrations of various salt solutions. The purpose of this method of preparation was to make the wax and pectin components constant factors and to remove surface sugar content as a variable.

MATERIALS AND METHODS

Cotton samples. The cotton cv. FiberMax 832 (Bayer CropScience; Research Triangle Park, NC) used in this study was grown in Georgia during the 2003 crop year. Prior to treatment, the cotton was washed with deionized water at 21 °C in sequential steps until the resulting solution exhibited no conductivity due to naturally occurring surface electrolytes and no sugar content as measured by a previously described method (Gamble, 2001). The washed cotton samples were treated with the various electrolyte

solutions and oven dried at 105 °C. Subsequently, the samples were reconditioned at 65% relative humidity and 21 °C prior to performing subsequent measurements. The micronaire of the cotton (ASTM, 1997) was 3.56 and remained constant following all treatments.

Modification of surface electrolyte content. Previous research established that the soluble cation content present on cotton fiber is comprised primarily of potassium (Brushwood and Perkins, 1994). HPAEC research performed in this laboratory has established that the predominant anions are malate, chloride, and sulfate (unpublished data, 2005). Using this information as a starting point, the pre-washed cotton samples were immersed in solutions of potassium malate (K_2 Malate; J.T. Baker Chemical Co.; Phillipsburg, NJ), potassium chloride (KCl; Sigma Chemical Co.; St Louis, MO), potassium sulfate (K_2SO_4 ; J.T. Baker Chemical Co.), sodium chloride (NaCl, Sigma Chemical Co.), sodium acetate (NaOAc, Sigma Chemical Co.), lithium chloride (LiCl, J.T. Baker Chemical Co.), and tetraethylammonium acetate (TEAA, Sigma-Aldrich Chemical Co. St. Louis MO). Instead of using a wetting agent to effect solution wetting, the samples were repeatedly agitated manually to remove air and to allow wetting of the cotton surface by the immersion solution. After thorough wetting, each sample was squeezed manually to remove most of the retained solution. Typically, the cotton took up two times its own weight of the solution. Next, the cotton was opened by hand and placed in a forced draft oven at 105 °C for 2 hr to completely dry the sample, after which all samples were allowed to recondition at 65% relative humidity and 21 °C for at least 16 hr prior to testing.

Moisture determination. Moisture determinations on each of the treated cotton samples were performed three times according to standard test methods (ASTM, 2001).

Conductivity measurement. Cotton samples were extracted using 20 ml of deionized water per gram of cotton, with three replicates performed for each of the treated cotton samples. Each sample was agitated with a glass rod in order to promote wetting of the cotton surface. The resultant wetted sample was allowed to sit for 15 min before being wrung out. The resulting extract was then subjected to conductivity measurements. Conductivity measurements, reported in microsiemens per centimeter ($\mu\Omega^{-1} \text{ cm}^{-1}$), were performed on a Myron L Company Model EP conductivity meter (Carlsbad, CA).

Friction measurement. Four replicates for each treated cotton sample were evaluated for fiber friction using the Rotorring 580 (Spinlab; Knoxville, TN). Slivers were approximately 208 g/m. Results of this measurement, reported in Joules (J), were converted to energy required to open a single fiber from the assembly using a previously described calculation (Gamble, 2004).

Statistics. All regression analyses were performed using SigmaPlot 8.0 (SPSS Science; Chicago, IL). One-way ANOVA were performed using SigmaStat 3.0 (SPSS Science). Means were separated using Duncan's Multiple Range Test ($P \leq 0.05$).

RESULTS AND DISCUSSION

A series of solutions of known concentration were prepared for each electrolyte in deionized water. The relationships between electrolyte concentration in water solution and the solution conductivity are shown in Figure 1. Within the concentration ranges evaluated, the correlations between conductivity and molar concentration were linear ($R^2 = 0.99$). This allows the conductivity measurement to be converted to molarity for each of the salts used in this study using the linear relation $y = mx + b$ (Table 1). The molarities were subsequently converted to moles per gram of treated cotton fiber based on this calculation. Conductivity values and the moles per gram of fiber are shown in Table 2.

The relationship between surface electrolyte content, presented as moles per gram of treated cotton (mol/g), and single fiber friction as measured by the Rotorring for the samples treated with sodium acetate, potassium sulfate, and potassium chloride are shown in Figure 2. The data for sodium acetate and potassium sulfate indicate a linear relationship ($R^2 = 0.98$ and 0.99 , respectively) between single fiber friction and the amount of electrolyte present on the surface of the fiber. The relationship between fiber friction and surface concentration of potassium chloride over the range of concentrations tested did not change. The decrease in fiber friction associated with increasing sodium acetate and potassium sulfate concentrations is tentatively presumed to be the result of anti-electrostatic properties, i.e. the ability of the specific cation-anion combination to dissipate electrostatic charge created in the processing environment. The reasons for the lack of anti-electrostatic action with potassium chloride are unknown, but may be related to the fact that potassium and chloride exhibit similar

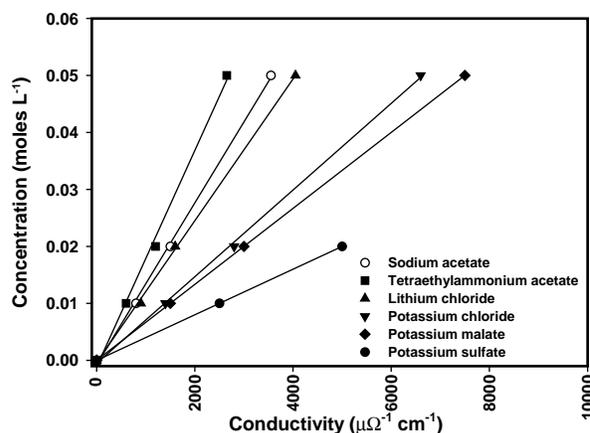


Figure 1. Solution conductivity as a function of electrolyte concentration for the six salts used to treat cotton fiber.

Table 1. Parameters used to fit the data presented in Figure 1 to the linear equation ($y = mx + b$, where y = concentration and x = conductivity)

Salt	Slope	Intercept	R^2
Sodium acetate	1.427×10^{-5}	-9.4×10^{-4}	0.99
Tetraethylammonium acetate	1.914×10^{-5}	-7.2×10^{-4}	0.99
Lithium chloride	1.237×10^{-5}	1.0×10^{-5}	0.99
Potassium chloride	7.527×10^{-6}	3.2×10^{-4}	0.99
Potassium malate	6.667×10^{-6}	9.9×10^{-4}	1
Potassium sulfate	3.796×10^{-6}	6.6×10^{-4}	1

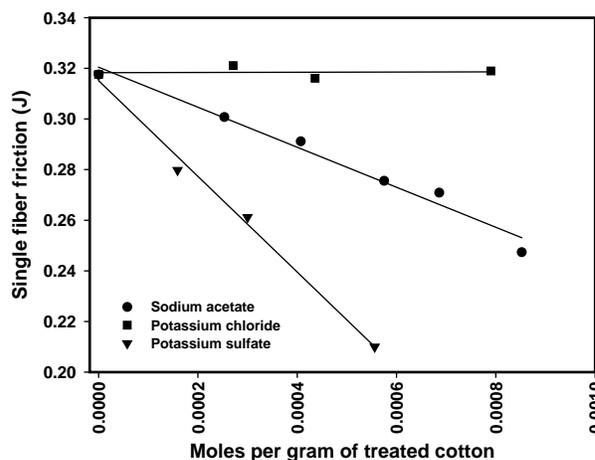


Figure 2. Single fiber friction as a function of surface concentration for the three non-deliquescent salts used to treat cotton fiber.

ionic radii that results in a relatively weak polarization of the charge with this cation-anion combination. For potassium malate and lithium chloride, an initial decrease in fiber friction at lower surface concentrations, due presumably to an anti-electrostatic effect, changed to a rather dramatic increase in friction at

higher concentrations (Fig. 3). For tetraethylammonium acetate, a substantial increase in fiber friction was evident even at a low surface concentration (Fig. 3). Since the measured friction value is a combination of fiber-to-fiber and fiber-to-metal interactions, an additional measurement was required in order to explain the observed variation in fiber friction as a function of surface electrolyte. The width of the formed sliver is a function solely of fiber-to-fiber cohesion, and each of the electrolyte treatments decreased sliver width (Table 2). Sliver width as a function of increasing electrolyte surface concentration for potassium sulfate and potassium malate is shown in Figure 4. All of the salts used in this study exhibited similar behavior. Sodium acetate had the smallest effect on sliver width and tetraethylammonium acetate had the greatest. The effect of surface salts on sliver width may be in part due to a decrease in inter-fiber electrostatic repulsive forces that arise because of the action of fibers being drawn across one another during the opening of the sliver. This effect may be alternatively viewed as an increase

in fiber-to-fiber friction. If this were the only friction variable involved with the Rotorring measurement, it might be expected that all of the salts used in this

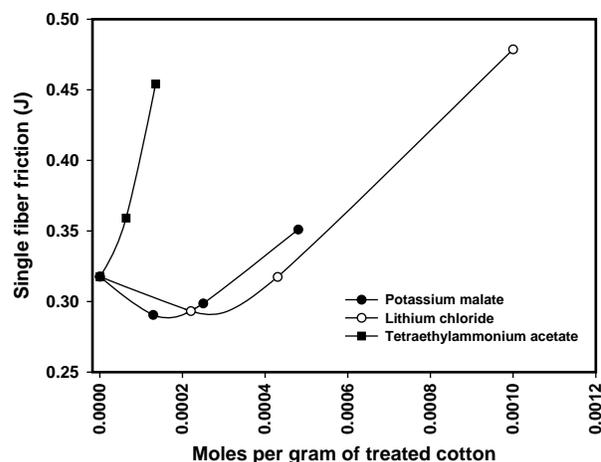


Figure 3. Single fiber friction as a function of surface concentration for the three deliquescent salts used to treat cotton fiber.

Table 2. Physical and chemical fiber properties of the cotton subjected to different concentrations of the six salt treatments

Treatment	Conductivity ($\mu\Omega^{-1} \text{ cm}^{-1}$)	Salt content (moles/g fiber)	Single fiber friction (J)	Sliver width (cm)	Total moisture fraction, $[\text{H}_2\text{O}]_t$	Salt moisture fraction, $[\text{H}_2\text{O}]_s$	Salt moisture (moles/g fiber)
Deionized H_2O	7 m	0.0	0.318 def	6.33 a	0.0615 h	0.0000	0.0
0.1M NaOAc	890 j	2.3×10^{-4}	0.301 d-g	5.63 b	0.0693 fg	0.0076	4.2×10^{-4}
0.2M NaOAc	1433 i	3.9×10^{-4}	0.291 e-h	5.55 b	0.0692 fg	0.0146	8.1×10^{-4}
0.3M NaOAc	2000 gh	5.5×10^{-4}	0.276 ghi	5.08 c	0.0717 ef	0.0200	1.10×10^{-3}
0.4M NaOAc	2416 f	6.7×10^{-4}	0.271 ghi	4.67 def	0.0833 c	0.0250	1.39×10^{-3}
0.5M NaOAc	3000 e	8.4×10^{-4}	0.248 i	4.8 de	0.0874 b	0.0303	1.68×10^{-3}
0.03M TEAA	203 l	6.3×10^{-5}	0.321 c	4.5 efg	0.0682 g	0.0079	4.4×10^{-4}
0.05M TEAA	390 k	1.4×10^{-4}	0.454 b	4.1 g-j	0.0737 e	0.0147	8.2×10^{-4}
0.1M KCl	1350 i	2.7×10^{-4}	0.321 de	4.7 def	0.0627 h	0.0026	1.4×10^{-4}
0.2M KCl	2867 e	4.4×10^{-4}	0.316 def	4.4 fgh	0.0635 h	0.0043	2.4×10^{-4}
0.5M KCl	5200 b	7.9×10^{-4}	0.319 def	3.8 jkl	0.0631 h	0.0056	3.1×10^{-4}
0.1M K_2SO_4	2267 fg	1.6×10^{-4}	0.280 f-i	4.7 def	0.0621 h	0.0025	1.4×10^{-4}
0.2M K_2SO_4	4133 c	3.0×10^{-4}	0.261 hi	4.4 efg	0.0618 h	0.0037	2.0×10^{-4}
0.5M K_2SO_4	7500 a	5.6×10^{-4}	0.210 a	4.0 h-k	0.0612 h	0.0060	3.3×10^{-4}
0.05M K_2Malate	967 j	1.3×10^{-4}	0.291 e-h	4.3 ghi	0.0635 h	0.0039	2.2×10^{-4}
0.1M K_2Malate	1867 h	2.5×10^{-4}	0.299 d-g	3.9 ijk	0.0642 h	0.0064	3.6×10^{-4}
0.2M K_2Malate	3600 d	4.8×10^{-4}	0.351 c-f	3.5 l	0.0738 e	0.0198	1.1×10^{-3}
0.1M LiCl	900 j	2.2×10^{-4}	0.293 e-h	5.1 cd	0.0743 e	0.0143	7.9×10^{-4}
0.2M LiCl	1733 h	4.3×10^{-4}	0.317 def	4.4 fgh	0.0792 d	0.0201	1.1×10^{-3}
0.5M LiCl	4033 c	1.0×10^{-3}	0.479 b	3.7 kl	0.1243 a	0.0703	3.9×10^{-3}

^z Means within a column followed by the same letter are not significantly different according to Duncan's Multiple Range test ($P \leq 0.05$).

study would cause increases in single fiber friction. Comparison of the behaviors provided in Figures 2 and 3, however, demonstrates that this is not the case. The fact that potassium sulfate and potassium malate exhibited similar behaviors regarding decreasing sliver width but very different behaviors in overall fiber friction indicates that fiber-to-metal friction is much more sensitive to the nature of the surface salt than fiber-to-fiber friction.

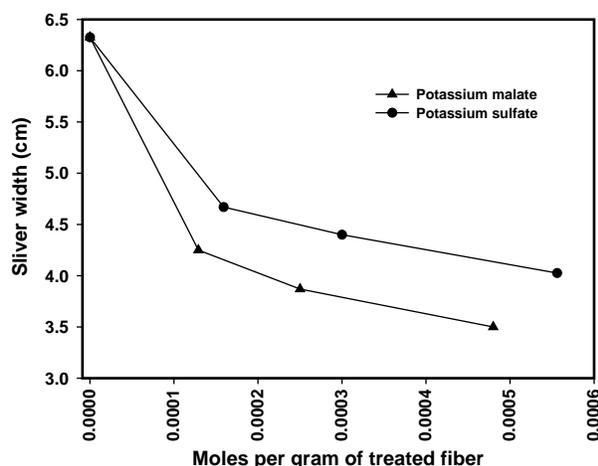


Figure 4. Rotorrying sliver width as a function of surface concentration for cotton treated with potassium sulfate and potassium malate.

One of the most obvious differences between the salts shown in Figure 2 and the salts shown in Figure 3 is the difference in their interactions with atmospheric moisture. The salts shown in Figure 3 (lithium chloride, potassium malate, and tetraethylammonium acetate) are deliquescent at conditions of 65% relative humidity and 21 °C. Previous work suggested that there is a relationship between moisture content and fiber friction, although this correlation is not necessarily independent of surface electrolyte content (Gamble, 2005). In order to further elucidate the relationship between surface electrolyte content and moisture content, a method which is capable of distinguishing between the moisture associated with the surface salts and the moisture associated with the cellulosic and pectic portions of the cotton fiber itself must be used. The observed weight fraction of the treated fiber due to moisture is a sum of the contributions of the surface salts and the moisture of the cotton fiber exclusive of the surface salts

$$[\text{H}_2\text{O}]_t = [\text{H}_2\text{O}]_f + [\text{H}_2\text{O}]_s, \quad [\text{Eq. 1}]$$

where $[\text{H}_2\text{O}]_t$ is the total moisture content as a fraction of the total weight of the fiber, $[\text{H}_2\text{O}]_f$ is the contribution from the fiber, and $[\text{H}_2\text{O}]_s$ is the contribution from the surface salts.

In order to determine how much water is associated with the surface salts, a series of equations must be used. $[\text{H}_2\text{O}]_t$ is determined from the moisture analysis of the entire sample, whereas $[\text{H}_2\text{O}]_f$ and $[\text{H}_2\text{O}]_s$ must be determined via calculation. Beginning with the relation

$$1 = [\text{fiber}] + [\text{H}_2\text{O}]_f + [\text{salt}] + [\text{H}_2\text{O}]_s \quad [\text{Eq. 2}]$$

and substituting with Eq. 1,

$$1 = [\text{H}_2\text{O}]_t + [\text{fiber}] + [\text{salt}]. \quad [\text{Eq. 3}]$$

$[\text{Salt}]$ is determined by multiplying the measured value of moles/g cotton by the formula weight of the salt, so that $[\text{fiber}]$ may be determined from

$$[\text{fiber}] = 1 - [\text{H}_2\text{O}]_t - [\text{salt}]. \quad [\text{Eq. 4}]$$

From Table 2 the measured moisture content of washed, untreated fiber is 0.0615, so using the relation

$$0.0615 = [\text{H}_2\text{O}]_f / \{ [\text{fiber}] + [\text{H}_2\text{O}]_f \} \quad [\text{Eq. 5}]$$

and substituting in Eq. 4, $[\text{H}_2\text{O}]_f$ is determined by

$$[\text{H}_2\text{O}]_f = \{ 1 - [\text{H}_2\text{O}]_t - [\text{salt}] \} / \{ 16.2602 - 1 \}. \quad [\text{Eq. 6}]$$

When Eq. 6 is substituted into Eq. 1, the value of $[\text{H}_2\text{O}]_s$, the moisture fraction associated with surface salts, may be calculated (Table 2). Division of this number by the formula weight of water then gives the number of moles of water per one gram of treated fiber (Table 2). When this value is divided by $[\text{moles salt/g fiber}]$ (column 3, Table 2), a resulting hydration number is provided for each of the salts (Table 3). Sodium acetate and potassium malate have very similar hydration numbers (Fig. 2 and 3). Sodium acetate, however, causes a linear decrease in single fiber friction as a function of increasing concentration, while potassium malate causes an initial decrease in fiber friction at lower concentrations that increases at higher concentrations. The explanation for this difference in behavior is related to the fact that potassium malate is deliquescent at the standard conditions used in this study, while sodium acetate remains solid. The liquid phase of water associated with potassium malate, as well as tetraethylammonium acetate and lithium chloride, appears to be responsible for the observed frictional behaviors

exhibited in Figure 3. This liquid phase present on the surface of the fibers apparently interacts with the metal surfaces of the Rotorrying via a hydrogen bonding mechanism, and a high surface tension effectively provides an adhesive effect, resulting in high fiber-to-metal friction.

Table 3. Calculated hydration numbers and observed deliquescence properties for salts on treated cotton fiber conditioned at 65% relative humidity and 21 °C

Salt	Hydration number	Deliquescence
Sodium acetate	2.0	No
Tetraethylammonium acetate	6.4	Yes
Potassium chloride	0.5	No
Potassium sulfate	0.7	No
Potassium malate	1.8	Yes
Lithium chloride	3.4	Yes

It has previously been shown that water extracts of raw cotton fiber grown under similar environmental conditions exhibit conductivity proportional to fiber maturity (Gamble, 2005). In addition, it was shown that when open bolls of cotton experience rainfall prior to harvest, both the conductivity of the water extract and the moisture content of the fiber decrease concomitantly. This indicates that cotton fiber has a naturally occurring surface coating of hygroscopic electrolytes at concentrations that can be altered by rainfall. It was further demonstrated that an increase in fiber friction accompanied these decreases in both conductivity and moisture content. These effects make sense in light of the results of the current study, if it is understood that the natural salt content of the cotton fiber, comprised primarily of potassium chloride, potassium sulfate, and potassium malate, may not be homogeneously distributed across both the inner and outer fiber surfaces. Specifically, the deliquescent salt potassium malate is known to be present on the inner surface, or lumen, of the fiber where it provides turgor pressure for the growing fiber (Dhindsa et al., 1975). A heterogeneous distribution of salts on the inner versus outer surfaces of the fiber might be expected to display a different dielectric behavior than would a homogeneous distribution, especially if this also affects the surface distribution of moisture. The implications of a homogeneous versus a heterogeneous distribution of surface salts

on the physical and electrostatic cohesive properties of the cotton fiber during processing are currently unknown. In order to answer these questions, the precise distributions of all of the naturally occurring salts on the cotton fiber must be further elucidated, which is the subject of a continuing investigation.

CONCLUSIONS

A single cultivar of cotton was subjected to treatment in different electrolyte solutions at different concentrations, in which the frictional behavior of the cottons was measured using the Rotorrying. Results indicated that various electrolytes on the surface of the cotton fiber may lead to either an increase or a decrease in fiber friction, with the more hygroscopic electrolytes in general being responsible for increases in fiber-to-metal friction due to surface tension. Fiber-to-fiber friction was increased by all surface electrolyte treatments, implying that electrolyte content in conjunction with surface moisture confers anti-electrostatic properties, increasing the coherence between individual fibers. The results of the present study hold a number of implications for cotton processing performance. The amounts and types of surface salts present on cotton fiber appeared to play a major role in both fiber-to-fiber and fiber-to-metal friction. A decrease in these surface salts due to environmental conditions resulted in decreased fiber coherence as a result of electrostatic repulsive forces between fibers, possibly leading to decreased yarn strength and increased imperfections. Increased fiber-to-metal friction resulting from the loss of non-hygroscopic salts from the outer fiber surface may lead to increased short fiber content as a result of the higher force required to open the fibers. The environmental conditions responsible for these changes in surface salt content cannot be controlled, so that a crop experiencing high amounts of rainfall may naturally exhibit difficulties in processing. Other difficulties of processing are due to a change in the surface chemical characteristics of the fiber. Awareness of these difficulties may allow fiber processors to compensate with adjustments to the processing equipment itself or by the application of oversprays, which would bring the surface characteristics of the fiber back to pre-weathering condition. The utility of both of these strategies are currently under investigation in this laboratory.

REFERENCES

- American Society for Testing and Materials (ASTM). 1997. Standard test method for fiber cohesion in roving, sliver, and top in dynamic tests (D 4120). *In Annual Book of ASTM standards*, Vol. 07.02. ASTM, West Conshohocken, PA.
- American Society for Testing and Materials (ASTM). 1997. Standard test method for micronaire reading of cotton fibers (D1448-97). *In Annual Book of ASTM Standards*. Vol. 07.01. ASTM, West Conshohocken, PA.
- American Society for Testing and Materials (ASTM). 2001. Standard test method for moisture in cotton by oven drying (D2495-01). *In Annual Book of ASTM Standards*. Vol. 07.01. ASTM, West Conshohocken, PA.
- Brushwood, D.E and H.H Perkins. 1994. Determining the metal content of cotton. *Textile Chemist and Colorist* 26(3):32-35.
- Cui, X.L., J.B. Price, T.A. Calamari and J.M. Hemstreet. 2002. Cotton wax and its relationship with fiber and yarn properties. Part I: wax content and fiber properties. *Textile Res. J* 72(5): 399-404.
- Dhindsa, R.S, C.A. Beasley and I.P. Ting. 1975. Osmoregulation in cotton fiber. Accumulation of potassium and malate during growth. *Plant Physiol.* 56:394-398.
- El Mogahzy, Y.E. and R.M. Broughton. 1993. A new approach for evaluating the frictional behavior of cotton fibers. Part I: fundamental aspects and measuring techniques. *Textile Res. J.* 63(8): 465-475.
- El Mogahzy, Y.E. and K.Q. Robert. 1992. Descriptive evaluation of fiber/machine interaction in spinning. p. 1277-1281. *In Proc. Beltwide Cotton Conf.*, New Orleans, LA. 10-14 Jan 1992. Natl. Cotton Counc. Am., Memphis, TN.
- El Mogahzy, Y., R. Broughton and H. Guo. 1997. Cotton fiber friction: The unknown quality of cotton. p. 545-552. *In Proc. Beltwide Cotton Conf.*, New Orleans, LA. 7-10 Jan. 1997. Natl. Cotton Counc. Am., Memphis, TN.
- El Mogahzy, Y.E., R. Broughton and Q. Wang. 1995. 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. *Int. Nonwovens J.* 7(1): 26-33.
- Gamble, G.R. 2001. Evaluation of an enzyme-based method for the detection of stickiness potential on cotton lint [Online]. *J. Cotton Sci.* 5:169-173. Available at <http://www.cotton.org/journal/2001-05/3/169.cfm>
- Gamble, G.R. 2004. Implications of surface chemistry on cotton fiber processing [Online]. *J. Cotton Sci.* 8:198-204. Available at <http://www.cotton.org/journal/200408/3/198.cfm>
- Gamble, G.R. 2005. Cotton fiber chemical differences and their effect on friction behavior: a comparison of two crop years in the ATMI/ARS leading cultivars study [Online]. *J. Cotton Sci.* 9:56-64. Available at <http://www.cotton.org/journal/2005-09/1/56.cfm>.
- Ghosh, S., J.E. Rodgers and A.E. Ortega. 1992. Rotor ring measurement of fiber cohesion and bulk properties of staple fibers. *Textile Res. J.* 62(10):608-613.
- Graham, J.S. and C.K. Bragg. 1972. Draft force measurement as an aid to cotton spinning. *Textile Res. J.* 42(3): 175-181.
- Lord, E. 1955. Frictional forces between fringes of fibers. *J. Textile Inst.* 46:41-58.
- McAlister, D.D., III, J.D. Bargeron and L.C. Godbey. 2003. Using cotton sliver draft force to evaluate textile processing efficiency, Part I. *Appl. Eng. Agric.* 19(6):