Mechanics of the Extension of Cotton Fibers. I. Experimental Studies of the Effect of Convolutions

J. W. S. HEARLE and J. T. SPARROW, *Department of Textile Technology, University of Manchester Institute of Science and Technology, Manchester, England*

Synopsis

Cotton fibers have structure at many levels. This paper is concerned with the effect of gross convolutions on tensile properties. Experiments with rubber tubes show that convolutions result from the collapse of a twisted hollow tube. In cotton, the convolutions will reverse at the helix reversals. Extension of cotton fibers and of nylon models shows that the initial easy extension is due to the untwisting of convolutions. If the amounts of S- and Z-twist are different, the lesser part will become completely untwisted. Fibers stretched in water and then dried are without convolutions and are stiffer. Optical and SEM observations illustrate the behavior.

INTRODUCTION

Like most natural polymer systems, the cotton fiber has structure at a number of levels, all of which play a part in determining the mechanical and other properties of the fiber. Consequently any explanation of properties must take account of a number of different features ranging from molecular properties to the overall form of the fiber. This pair of papers aims to do so in a qualitative and quantitative way in regard to the behavior of cotton fibers in simple extension.

There have been many experimental investigations of the tensile properties of cotton, noted in textbooks,[1] and of their correlation with other measurements. Meredith[2–4] examined a wide variety of types of cotton fiber and found considerable differences. The stress-strain curve is slightly concave to the extension axis, and both strength and stiffness are found to be correlated with molecular orientation, which is itself related to apparent spiral angle. However, it has now been shown[5,6] that the spiral angle is constant within the range 20°–23°, but that apparent differences are due to convolutions. This had been proposed much earlier by Meredith.[4] Various studies relevant to the relation between tensile properties and structure are summarized in the Appendix.

Current views of the structure of a cotton fiber[7,8] indicate that within the primary wall, the bulk of the fiber consists of a secondary wall of cellulose in which microfibrils spiral around the fiber at an angle which is about 21° but which changes slightly in magnitude between the outside and the inside and, more important, reverses direction at frequent intervals along the fiber. It is not clear whether the microfibrils contain between 100 and 150 chains or whether this observed feature is composed of four subunits. In one sense, the fiber is 100% crystalline in that the disorder, which leads to a density equivalent to about two-thirds crystalline, derives from some internal defects within the fine crystalline microfibrils and the mismatch of their packing. The molecular chain axes

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are aligned with the axes of the microfibrils. At the center of the growing fiber there is a lumen which remains as a cylindrical void at maturity. On drying, the fiber collapses, flattening the lumen, taking up a convoluted ribbon form, and causing some disturbance of the fine structure.

Theoretical interpretation of the tensile properties of cotton and other plant fibers[9,10] has previously applied the methods of twisted yarn mechanics to determine the effect of spiral angle on the modulus of a helical assembly of crystalline fibers, allowing for possible volume changes through interaction with the bulk modulus. This analysis fits results reasonably well for a number of plant fibers with helix angles ranging from 10° to 45°, if the tensile modulus of crystalline cellulose is taken to be 2300 kg/mm^2 and the bulk modulus to be greater than 100 kg/mm^2,[10] but shows considerable divergence from some of the cotton fiber results and would not explain the nonlinearity of the cotton stress-strain curve. These differences will be due to the neglect of other structural features such as reversals and convolutions. Meredith[11] shows that the dynamic modulus of dry stretch-mercerized cotton fibers, with spiral angles between 18° and 36°, does fit the theoretical prediction closely with an assumed tensile modulus similar to that calculated for crystalline cellulose: the stretch-mercerizing would remove the influence of convolutions.

EXPERIMENTAL OBSERVATIONS

Study of Convolutions

Figure 1 shows SEM views of convoluted cotton fibers. In its simplest form, the convolution consists of a rotation through 180° (some workers adopt 360° as a definition) of the whole cotton fiber regarded as a flat ribbon, but there is much variation of form, and in many places the fiber takes up a wrapped ribbon form rather than a twisted form. In connection with studies of twisted yarns, Hearle and Bose[12] showed that these were alternative ways in which a ribbon

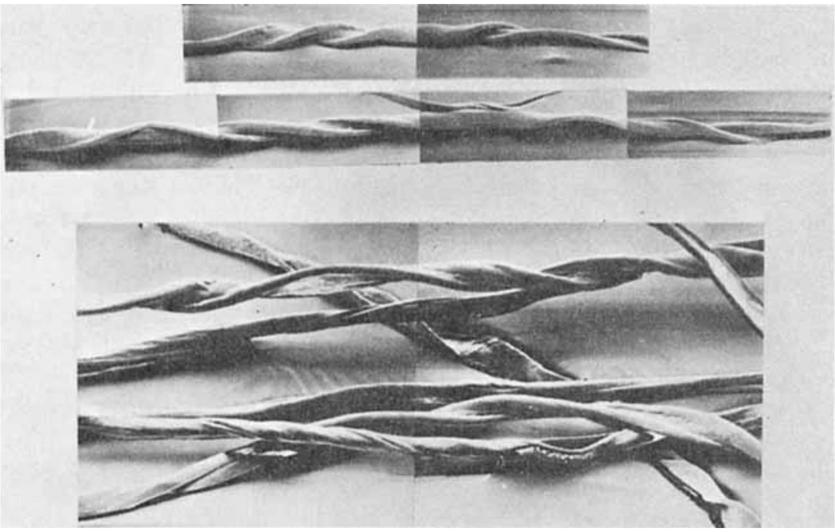

Fig. 1. SEM views of convoluted cotton fibers.

can accommodate twisting. The pitch of the convolutions depends on ribbon width and wall thickness.

There has been considerable speculation about the origins of convolutions, but it seems certain that they arise in order to relieve internal stresses during the drying and collapse of the cotton fiber. Although a detailed analysis of the mechanics would be difficult, a simple experiment shows that the effect occurs naturally without any need to specify unusual features of internal structure.

If an ordinary rubber tube [Fig. 2(a)] is evacuated, it collapses to give a flat ribbon [Fig. 2(b)]. But if the tube is twisted before it is evacuated, it then forms a convoluted ribbon [Fig. 2(c)], and furthermore, the collapse relieves to a considerable degree the torque required to twist the tube. It should be noted that no twisting occurs during the collapse: it is merely that the line of collapse follows the helix of the previously imposed twist.

Consequently it can be expected that the spiral structure would bias the collapse of cotton fibers to form convolutions, which would tend to alternate in sense as a result of the reversals. The convolutions will form during the early stages of drying as liquid water is lost and then be set into the structure by further drying and stress relaxation. The convoluted ribbon is the natural state of the cotton fiber free of stress, once it has been dried for the first time.

Observation of Fiber Extension by SEM

An extensometer stage was fitted in the scanning electron microscope in order to observe cotton fibers during extension. The fibers were impregnated with Duron antistatic agent and would, of course, dry out in the vacuum of the SEM. Test specimens were 0.5 or 1 mm in length. Other details of the experimental procedure are given elsewhere.[13]

The fiber specimen was examined along its length, and usually a convolution reversal, which would correspond to a fiber reversal, was found within the length. Attention was concentrated on this region as a likely place of fracture, although in fact the actual fracture was found to occur too rapidly to be observed. The fiber was then observed as it was successively extended in steps.

With the convolution reversal in the center of the screen and the extension being carried out, the fiber is seen to rotate about its axis at the reversal. As the

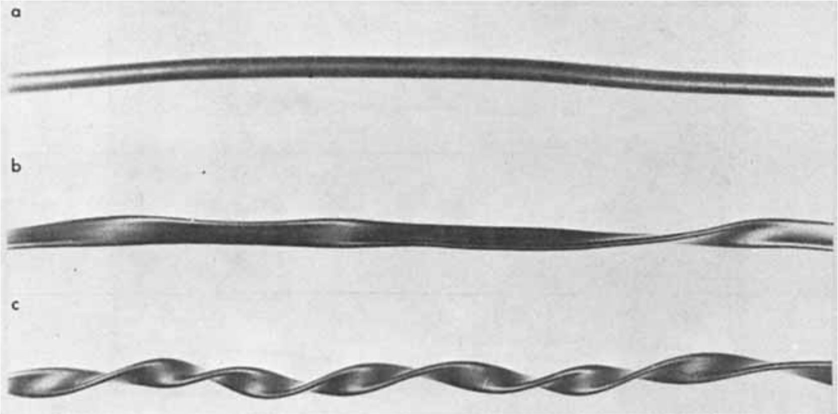

Fig. 2. Rubber tube before collapse (a); collapsed (b); twisted and then collapsed (c).

extension proceeds, this untwisting continues until the fiber is completely without twist when fracture occurs. For every 180° of rotation, the number of convolutions is reduced by two, one S and one Z on either side of the reversal. The convolution angle decreases due to the lower number of convolutions per fiber length and also due to the extra fiber length created as a result of the untwisting. This extension process is illustrated in the series of micrographs in Figure 3, each taken at a different extension. For the occasional fiber length mounted in the jaws which had no reversal, this deconvolution process did not occur. It is not possible for the above-described untwisting to occur unless a reversal is present.

The previous description concerns the extension of raw cotton. With cross-linked cotton, a similar observation is made. The fiber begins to rotate about its axis and untwist, but fracture usually occurs before the fiber is completely untwisted.

Real-time TV viewing was not available, but time-lapse cinematography was used according to the method of Hearle et al.[14]

The results obtainable are extremely useful, and the extension process of cotton can only really be appreciated by observing it in motion. The still micrographs do not do the phenomenon justice. The rotation of the fiber about its axis during extension is clearly visible, and the fiber continues to untwist up until the moment of fracture, where it is a straight, flattened tube without twist. When projected, one can see crack development just before fracture; and then by examining individual frames just before the time of fracture, one can see that the fracture

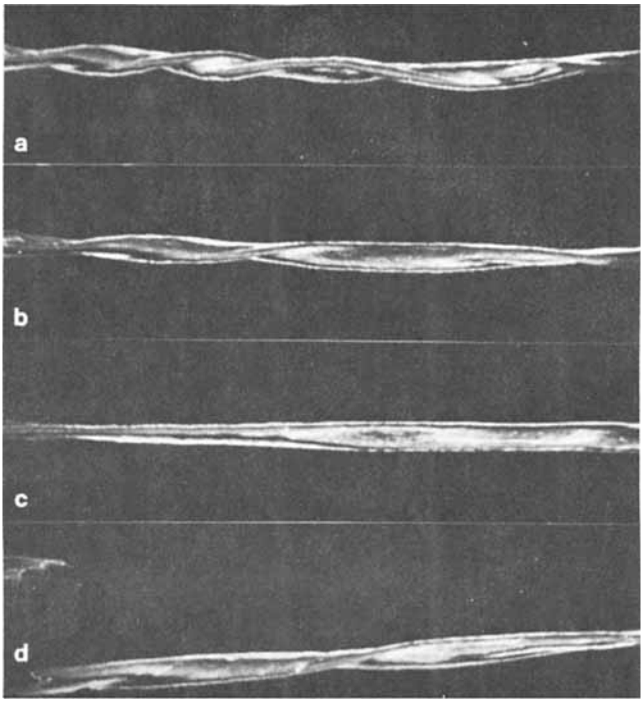

Fig. 3. Cotton fiber extended in the SEM: (a) before extension; (b) at 3.8% extension; (c) at 6.4% extension; (d) fracture at 7.4% extension (note rupture near left end).

mechanism proposed by Hearle and Sparrow[15] does in fact occur. A spiral crack develops, and then a shearing action completes the fracture by a breakage of fibrils between the ends of the crack. Fracture (or crack development) is probably aided by the untwisting of the convoluted structure. A better word to use might be "unbending," since as was pointed out earlier, some convolutions are in a wrapped form and not a true twist of the ribbon.

It was noticed that on some thick-walled or almost circular fibers, all of the convolutions were not removed at the time of fracture. This is also true for crosslinked fibers. Any fibers having folds or bends in them would fracture at the fold or bend, indicating that this is a source of weakness.

Examples from the motion picture recordings are not presented due to the great loss of detail which occurs when these negatives are reproduced.

Observations of a Model

In order to observe the deconvolution effect on a larger scale, a model was constructed. This consisted of a 44-cm-long strip of drawn nylon sheet, 2 mm wide, which had been clamped at the center, twisted in opposite directions in each half, and then heat set in an oil bath.

Several of these models with equal S and Z twists were made but with each having a different amount of twist. This gives models with different convolution angles, which would correspond to different varieties of convoluted cotton fibers, each having a different convolution angle. Other strips were twisted and set with more than one reversal, with unequal lengths of S and Z twist, and with a different convolution angle between the two types of twist.

The models were then extended with an Instron tensile tester. The results are shown in Figure 4, and as can be seen from the graph, the strip with the greatest amount of twist has the lowest initial modulus and is more extensible. There is thus an analogy between the twisted nylon strips and cotton fibers. Cotton fibers having a high convolution angle will have a lower initial modulus but will be more extensible, while those with a low convolution angle will have a high initial modulus and be less extensible.

If we look back at the x-ray work, in the light of Hebert's[5] and Ingram's[6] findings, we now can explain the correlations which have been established. The key to this whole modulus/extensibility phenomenon is the convolution reversal. Without the reversal the deconvolution effect could not occur. The fiber will certainly extend, thereby reducing the convolution angle, but deconvolution will not and cannot occur unless there is a reversal present.

Another important consideration is the amount of S and Z twist present. Orr et al.[16] observed the untwisting of cotton fibers during the application of a freely hanging load. If the fiber untwisted clockwise (as viewed from below), there was a net length of Z spiral and vice versa. Figure 5(a) shows part of a nylon model 44 cm long but with a reversal at 14 cm, which gives 14 cm of S twist (the minor twist) and 30 cm of Z twist (the major twist). (The entire model is not shown here because the great length-to-width ratio prohibits photographing it so as to show both the twist and the entire length.) As this strip is extended, the convolution angle of the minor twist reduces more rapidly than the convolution angle of the major twist. As is shown in Figure 5(b), when all of the minor twist is removed, that part of the fiber having the major twist remains convoluted but with

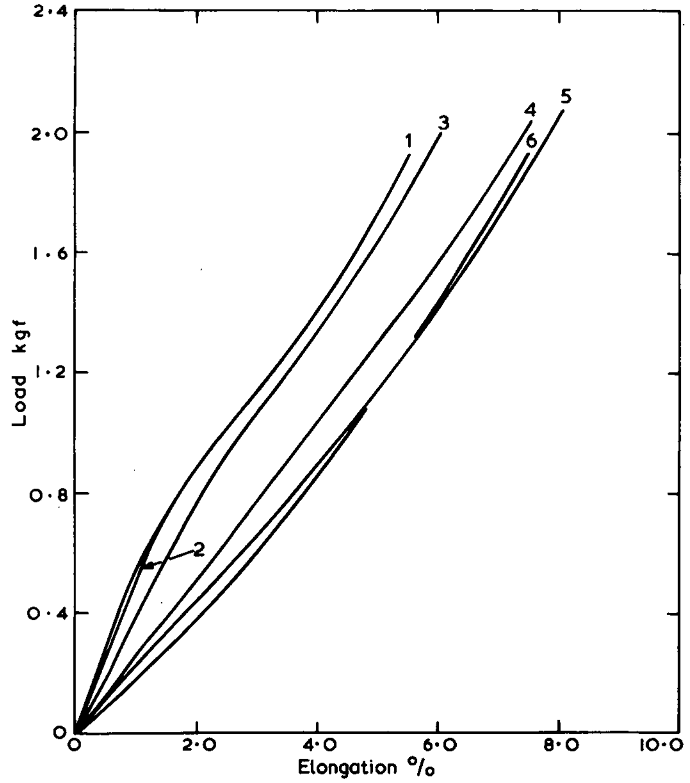

Fig. 4. Load-extension curves for the nylon models: (a) no twist; (2) 0.10; (3) 0.21; (4) 0.31; (5) 0.38; (6) and 0.41 radian/mm.

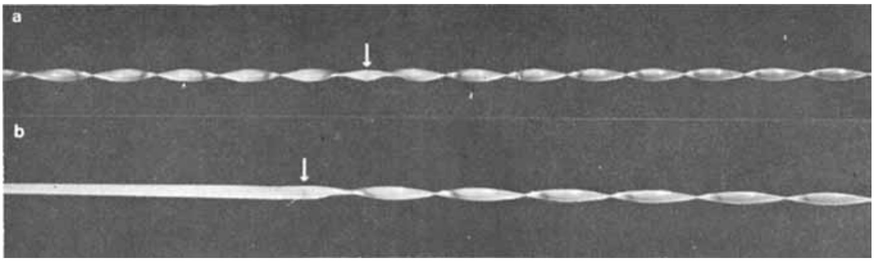

Fig. 5. A nylon model having major and minor twist: (a) before extension; (b) extended so that the minor twist is removed. The arrow shows the reversal position.

a greatly reduced convolution angle. Therefore, we can say that the total extension (due to convolution removal) of the strip is limited by the minor twist. Once all of the minor twist is removed, the deconvolution effect cannot occur, and hence any extension which is a result of deconvolution must end. If we extend this strip even further, the major twist (Z twist) is induced into what was the minor twist region of the strip. This may lead to fracture.

Two other strips were made, one which had 10 cm of Z twist, 24 cm of S twist, and 10 cm of Z twist; and another which had 15 cm of S twist, 14 cm of Z twist, and 15 cm of S twist. In both cases the S twist is the major twist, since a greater length of the strip is of this type of twist. As these strips are extended, the angle of the minor twist (Z twist) reduces to zero, while the major twist regions remain convoluted but with a reduced convolution angle.

We can now envisage a situation in the cotton fiber where a varying convolution angle, unequal amounts of S and Z twist, or a combination of the two influence the extensibility of the fiber as well as the fiber modulus. An ideal fiber would have a constant convolution angle throughout and equal portions of S and Z twist.

Observations of Stretched Cotton Fibers

It is well known that cotton fibers of different varieties have different stress-strain curves. It was decided to try to show that fibers of three different varieties have very similar tensile properties when tested in the deconvoluted state. The three varieties chosen for one experiment were Acala 1517, Menoufi, and Deltapine. Their strengths and elongation to break before treatment are given in Table I. These results were based on 25 individual tests for each variety, with the fibers being tested at a 1-cm gauge length and at 65% relative humidity (R.H.).

Ten fibers from each variety were mounted between metal tabs with Durofix so as to give a 1-cm test length. With the fiber immersed in water, it is extended with an Instron tensile tester to a load of 2 g and then held at this load for approximately 5 min. While still under this load, the water is drawn off and the fiber allowed to dry in the extended condition. The optical micrographs in Figure 6 show typical fibers before and after this treatment. As can be seen, the fibers that have been stretched in water and then dried in that condition have few or no convolutions, while the normal fibers have many. It should be also noted that the fibers are much stiffer after the treatment in water.

Each fiber length is measured after the treatment, and the fibers extended to break at 65% R.H. Table I shows that the fiber elongation has decreased considerably in each case. We attribute this decrease mainly to the fact that the treatment in water has deconvoluted the fiber and that the extra elongation made possible by the deconvolution effect is not present. It also shows that fibers whose elongations were previously very different are now relatively the same. It is interesting to note that the elongation of the Menoufi variety does not exactly fall into line with the other two. This is attributed to the fact that only in this case was the water treatment and fracture at 65% R.H. carried out on separate days. These fibers probably had time to regain some convolutions during this period.

The differences in elongation before the water treatment are mainly due to the different convolution angles between the varieties and hence different

TABLE I

Properties of Three Fiber Types Before and After Water Treatment

Fiber type	Mean breaking extension, %		Mean breaking load, g		Mean permanent extension (%) due to treatment
	Before	After	Before	After	
Deltapine	11.1	3.6	4.7	6.8	11.4
Menoufi	8.2	4.9	5.7	8.4	7.0
Acala 1517	7.0	3.5	4.6	7.4	5.8

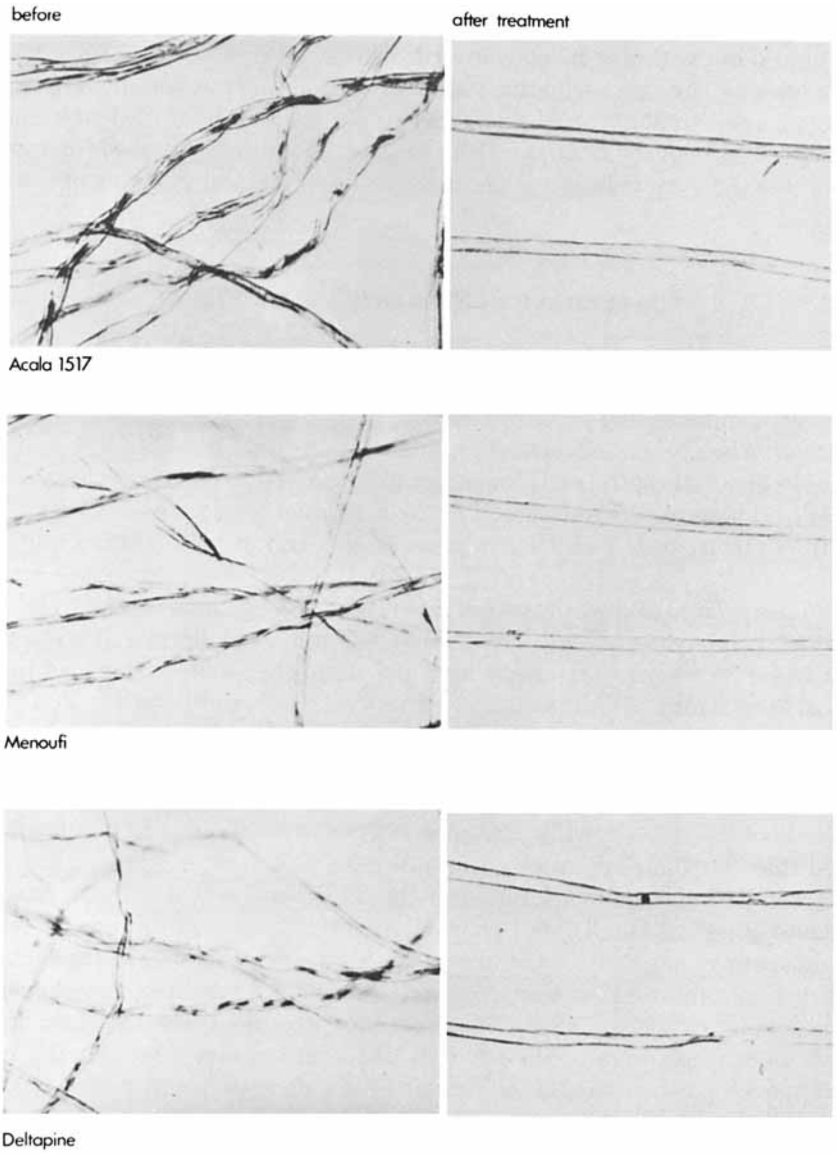

Fig. 6. Examples of three varieties of cotton before and after the water treatment used to remove the convolutions.

elongations to break. It should also be noted that the fiber strength has increased, indicating that during the extension process the deconvolution effect probably creates forces which readily lead to crack propagation and hence lower breaking loads for convoluted fibers. Indeed, many workers have correlated orientation with strength. If these orientation measurements are incorrect by a convolution angle factor, then there will be a correlation between strength and convolution angle. The initial moduli have been increased considerably, as shown in Figure 7 in the load-extension curves for Acala 1517 fibers before and after the treatment. It should be pointed out that during this water treatment it is possible to have reduced the fibrillar spiral angle, which would also lead to

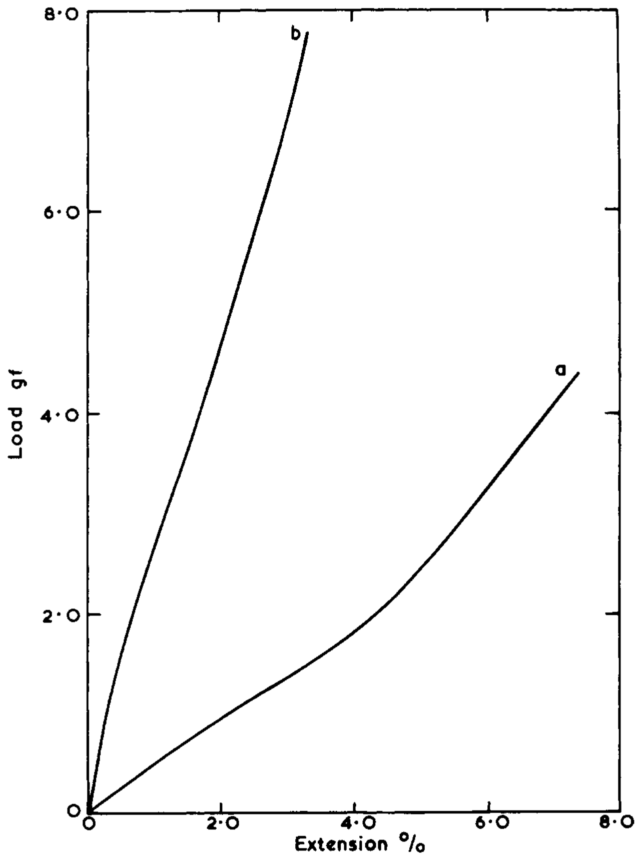

Fig. 7. Load-extension curves for two different single fibers with and without convolutions removed: (a) normal Acala; (b) Acala after treatment.

an increase in modulus. Meredith[11] has shown an increase in dynamic bending modulus as spiral angle decreases for tension-mercerized cotton fibers.

It is worth noting that the total extension to break of the water-treated fibers, namely, the permanent extension after the wet stretching plus the additional extension to break, is greater by 3.9%, 3.7%, and 2.3%, respectively, than the extension to break of the untreated fibers. In the untreated fibers, the straightening of the convolutions will lead to additional stresses which contribute to the cause of breakage; but the water treatment will remove the convolutions while allowing some slip of molecules and will stabilize the structure in a more favorable form which can sustain greater loads and extensions. The wetting may also relieve other internal stresses, by an annealing action, and the fiber will dry with the molecules in a form well suited to resisting breakage.

Observation of Spiral Structure Changes

Because of the deconvolution effect observed on fibers under an increasing tension, it was decided to show that a similar effect could occur in the fibrillar structure. A set of experiments was carried out on extending fibers in water. Ten single fibers were mounted between metal tabs so as to give a 5-mm gauge length. The total length of S and Z twist was measured for each fiber, which was then extended in water until a loading of 1 g was reached. The water was removed and the fiber dried while under this tension. The length of S and Z twist was again measured. This was repeated for loads of 2, 3, 4, and 5 g.

The twist, whether S or Z, was grouped into either major or minor twist depending on which made up a greater length of the fiber. The strain was then calculated for each type of twist (major or minor) at each loading in water and plotted against the particular load the fiber experienced in the water. Figure 8 shows the result. As can be seen from this graph, the major twist stops extending at about 6% extension, while the minor twist continues to extend. This extra extension of the minor twist is almost certainly due to a change in the spiral angle of the fiber parts making up the minor twist and accounts for the straightening of fibrils in alternating parts of the fiber, which has been observed previously for mercerized fibers fracture in water.

If these fibers are examined in the polarizing microscope, it can be seen in the minor twist that there is a straightening of the fibrils, as illustrated in Figure 9(a). At a reversal, one can see [Figure 9(b)] in partially polarized light that on one side of the reversal the cracks following the fibrils are at smaller angles than on the other side of the reversal. This illustrates that on extension in water, the cotton fiber is capable of extending more in one type of twist than the other by a mechanism similar to that described for convolutions because of the existence of fibrillar reversals and different lengths of S and Z twist. For equal lengths of S and Z twist the fiber would extend uniformly.

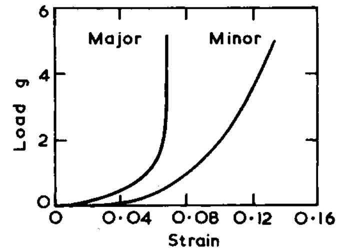

Fig. 8. Extension of the major and minor twist of a cotton fiber in water.

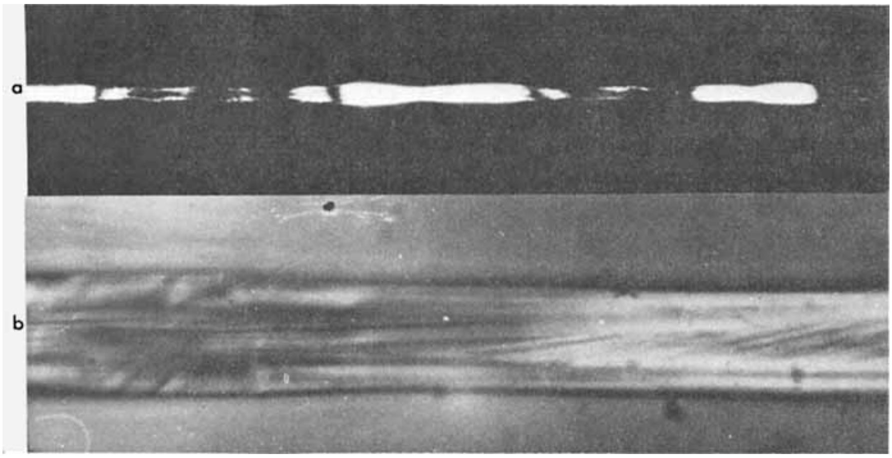

Fig. 9. Optical micrographs of cotton fibers stretched in water: (a) showing the straightening effect in the region of minor twist; (b) in partially polarized light, cracks are at different angles in the major and minor twist regions.

Too much importance should not be attached to this experiment, since it was not reproducible. The experiment is very time consuming, and fibers are accidentally broken in the process of taking measurements and mounting in the Instron. The experiment was repeated, but both the major and minor twist extended at the same rate after an initial difference in extension. The initial difference is probably due to convolutions. It has still been shown, though, that the minor twist is more susceptible to straightening when the fiber is under tension. This could lead to a stress concentration in these parts of the fiber, which in turn could lead to fracture.

Isings[17] has reported that studies by fluorescence microscopy indicate that when the cotton fiber is under stress, a small part of reversed spiral can originate between two reversals. Actually what was probably seen here was the straightening of fibrils in this region and not the formation of a reversed spiral.

CONCLUSION

The present work gives an experimental demonstration of the role of convolutions in influencing the extension of cotton fibers, leading to an easier incremental extension under low stresses with removal of convolutions than at higher stresses or, in other artificial circumstances, when convolutions have been removed. The observation that true spiral angles in cotton are almost constant can be reconciled with the large differences in mechanical properties and the correlation with apparent spiral angle by means of the influence of convolutions on both the latter effects. Convolutions, like an increase of true spiral angle, will reduce the resistance to extension. However, the quantitative effects will be different, and earlier theories based solely on helix angle in an unconvoluted tube cannot be expected to give precise agreement with experiment. The second paper in this pair will take up the influence of various factors on the theoretical modeling.

APPENDIX: SPIRAL ANGLE, REVERSALS, CONVOLUTIONS, AND MECHANICAL PROPERTIES

Other work of relevance to the relation between spiral angle, convolutions and tensile properties may be summarized as follows.

Year	Reference	Notes
1923	Denham[18]	Observed and classified convolutions.
1924	Clegg & Harland[19]	Convolution form.
1925	Balls[20]	Convolution reversals correspond exactly to spiral reversals, except when spiral reversals are too close together.
1930	Clark[21]	Prediction of the x-ray method as a useful tool for research in the cotton industry.
1933	Sisson & Clark (22)	Data, indicated a functional relationship between orientation and physical properties.
1934	Morey[23]	Orientations determined optically, but suggested that the x-ray method is preferred, since it uses a large number of fibers and average values are obtained.
1935	Morey[24]	Correlated orientation with strength.
1937	Sisson[25]	Correlated orientation with strength.
1938	Berkley & Woodyard[26]	Correlated orientation with strength.
1938	Conrad & Berkley[27]	Correlated orientation with strength and suggested the use of the x-ray method.

Year	Reference	Notes
1939	Berkley[28]	Tensile strengths predicted by the x-ray method.
1946	Meredith[3]	Correlated orientation with strength and initial Youngs modulus.
1948	Hassler et al.[29]	Correlated orientation with strength.
1948	Berkley[30]	Correlated orientation with strength.
1951	Meredith[4]	Correlated orientation with strength. Suggested that the x-ray angle can be modified by a change in convolution angle without a corresponding change in strength. Predictions by x-ray angle have only limited value. Suggested that the spiral angle in all cottons is the same. Found a correlation between convolution angle and x-ray angle.
1951	Wakeham & Spicer[30a]	Break at reversals shown by polarized light. Effect of various factors.
1953	Meredith[31]	Correlation between spiral angle and convolution angle. Found that if the convolution angle is subtracted from the x-ray angle, the difference is a constant at 21.7°, which suggested that the spiral angle of unconvoluted cotton is the same for all varieties. Correlated orientation with Youngs modulus and with strength.
1955	Wakeham & Spicer[31a]	Distribution of reversals and breakage.
1956	Hertel & Craven[32]	Correlated orientation with elongation and with strength.
1957	Rebenfeld & Virgin[33]	Correlated orientation with strength, modulus, and elongation.
1959	Orr et al.[34]	Correlated orientation with strength, Youngs modulus, and elongation. Shows there is a decrease in x-ray angle for tension-treated fibers.
1960	Betrabet et al.[34]	Correlated convolution angle with strength and x-ray angle.
1961	Orr et al.[36]	Correlated x-ray angle with strength, modulus and elongation. Showed that with a reduction in x-ray angle, there is a corresponding increase in strength and a decrease in elongation.
1961	Weiss et al.[37]	Correlated x-ray angle with secant modulus.
1963	Betrabet et al.[38]	Correlated orientation with strength. Agreed with Meredith's (21) result that if the convolution angle is subtracted from the spiral angle, the result is constant for all varieties of cotton.
1964	Betrabet & Iyengar[39]	Correlated convolution angle with strength.
1967	Joshi et al.[40]	Correlated x-ray angle with modulus, strength, and elongation.
1967	Hebert[41]	Illustrated that by using Hartshorne theory,[42] it can be shown that the spiral angle of all cottons is constant at 21.6°.
1967	Ducket & Tripp[43]	Using optical and x-ray methods, it was shown that the spiral angle is approximately 21.7°.
1968	Raes et al.[42a]	Distribution of reversals.
1970	Egle and Grant[44]	Correlated x-ray angle with strength, modulus, and elongation.
1970	Morosoff & Ingram[6]	Using optical and x-ray methods, it was shown that the spiral angle is constant between 20° and 30°.
1970	Hebert et al.[5]	Optical and x-ray methods showed the spiral angle to be constant at 21°–25°. Correlated convolution angle with x-ray angle and birefringence.

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