Effect of Yarn Geometry and Fiber Properties on Tensile Behavior of Cotton Yarns Swollen and Stretched in Aqueous Zinc Chloride

P. BHAMA IYER, S. SREENIVASAN, G. S. PATEL, K. R. KRISHNA IYER and N. B. PATIL*

Cotton Technological Research Laboratory (Indian Council of Agricultural Research),
Matunga, Bombay 400 019, India

SYNOPSIS

Single- and two-ply yarns of different counts were swollen slack under optimum conditions in aqueous zinc chloride and stretched back to original length. While two-ply yarns showed an improvement in tenacity that was less pronounced in finer counts, single yarns always showed a fall in tenacity. Various properties of the treated yarns like packing fraction, fiber and yarn orientation, cross-sectional morphology, etc. were evaluated to ascertain the likely factors responsible for the differential behavior of the chemically treated single- and two-ply yarns.

INTRODUCTION

In a previous communication,[1] we reported the changes in tensile and structural properties of cotton fibers brought about by swelling and stretching treatments in $ZnCl_2$. A spectacular improvement in tenacity occasioned by improved fibrillar orientation was found to result from these treatments. It is well known[2] that, besides fiber properties, yarn geometry plays a significant role in deciding the ultimate yarn properties. The present investigation was undertaken to examine how far yarn geometry influences the changes in the fine structural and tensile properties caused by $ZnCl_2$ treatment.

In the present investigation, single- and two-ply yarns of different counts were treated with aqueous $ZnCl_2$ under optimum conditions.[1] For the sake of comparison, samples were also treated in NaOH of mercerizing strength. Tensile and structural properties of the treated yarns and controls were measured by using appropriate techniques. The observed differential response of single- and two-ply yarns has been explained on the basis of changes in (1) fiber cohesion brought about by variations in fiber packing and (2) yarn orientation resulting from the swelling and stretching treatments.

EXPERIMENTAL

Materials and Methods

Control Samples

Fibers were spun in the conventional way on the ring frame by using cottons of appropriate staple lengths so single yarns of wide range of counts comprising 20^s, 40^s, 60^s, and 80^s could be obtained. Part of the yarns of each count was converted into two ply with a doubling ratio of 0.8 using a doubler. Both single- and two-ply yarns were later kiered in lea form in 1% NaOH at a pressure of 15 psi for 4 h. The kiered yarns were washed, soured in 2% acetic acid, washed further, and air dried. These kiered yarns formed the control for swelling treatments.

Swelling and Stretching Treatments

One lea from each yarn sample was swollen slack in aqueous $ZnCl_2$ solution (density: 1.834–1.850 g/cc; temperature 32 ± 1°C) for 30 min and then stretched back to original length in a hand-operated

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* To whom correspondence should be addressed.

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lea stretching device. Subsequently, the lea was washed in water (in the tensioned state) until free of the swelling agent, removed from the stretching device, and dried in air.

For alkali treatment, the leas were swollen in the slack state in aqueous NaOH (21% w/w; 30 ± 1°C) for 10 min and then stretched to original length. They were washed in water, soured in dilute acetic acid, and washed again before being removed from the stretching frame. The washed leas were allowed to dry in air.

Measurements on Yarns

Tensile Tests

The instron tensile tester (Model 1122) was employed for tensile tests. Yarns conditioned at 65% RH were tested at a gauge length of 25 cm with a pretension of 0.5 g/tex. The cross-head speed was so chosen that the breaking time remained within 20 ± 5 sec. The tenacity reported is the ratio of the average breaking load of 25 segments to the average tex value of the broken pieces. The initial modulus was calculated from the slope of the load-extension curve at a load of 0.5 g/tex. Stiffness reported is the ratio of the average tenacity to the average breaking extension.

Packing Fraction of Yarns

The ratio of the specific volume of the fiber to that of the yarn gives the packing fraction (PF) of the yarn. Accuracy of determining the PF depends on the reliability of the value of yarn diameter. A projection microscope having an attachment to guide the yarn under proper tension and thereby facilitate measurement at different places along the length was used for the purpose. Diameter was measured at 50 different places along the length at a magnification of about 250 ×. In the case of two-ply yarns, the widths in the broad and narrow regions were separately measured and referred to as major and minor axes of what was assumed to be an elliptical cross-section.

For comparison, the diameters for one set of two-ply yarns were obtained from cross-sections of the yarns embedded in a mixture of methyl and butyl methacrylate solutions. This method always gave marginally lower values for both diameters of two-ply yarns. However, the trend in the variations with the treatment was found to be the same.

Specific volume of yarn was calculated from the diameters and tex value while specific volume of fiber was taken as the reciprocal of fiber density. Values of fiber density assumed for raw and treated cotton were 1.54 and 1.52 g/cc, respectively.

X-Ray Orientation Measurements

The azimuthal intensity profiles of the (002) diffraction arcs from yarns were obtained by using a Philips X-ray generator and diffractometer accessories. A parallel array of yarns prepared with the help of a special device was mounted on a face plate kept normal to the collimated X-ray beam. A mounting tension of 0.5 g/tex per strand was applied during mounting of the yarn onto the face plate. The diffracted X-rays were received by a proportional counter set at an angle of $2\Theta = 22.8°$ corresponding to the (002) arc. The face plate was rotated in its own plane at the rate of one rev/h. For fibers removed from the treated yarns, the azimuthal intensity profiles were recorded essentially in the above manner, by mounting a highly parallelized bundle of fibers unravelled from the yarn.

The 50% X-ray angle (ϕ) and the orientation value ($1/\phi_{1/2}$) were calculated from the yarn and fiber bundle profiles using standard procedure.[3]

SEM Studies

Change in cross-sectional morphology brought about by the two swelling agents was studied by using scanning electron microscopy (SEM) (Cambridge Stereoscan S-150). Yarn segments were embedded in a mixture of butyl and methyl methacrylate solutions and cured for about 6 h at 60°C to get solid blocks from which cross-sections were cut with surgical blades. These sections were mounted on specimen stubs and sputter coated with gold before scanning in the microscope. Micrographs of yarn cross-sections were obtained with appropriate magnification.

RESULTS

Specific properties such as count, twist, tenacity, and elongation of the yarns of extreme counts used in the present study are given in Table I. The important fiber properties that decide the spinnability of the varieties of cotton used in preparing these yarns are also included in Table I. It may be noted that in the case of 80^s yarn there is significant improvement in tenacity on doubling, while no such change is found for the yarns of 20^s count.

Table I Properties of Cotton Fibers and of Yarns Spun Therefrom

	Fiber Data				Yarn Data			
			Tenacity (g/tex)					
Variety of Cotton	Length (mm)	Micronaire Fineness (μg/in)	T_0	$T_{3.2}$	Count (Ne)	Twist (tpi)	Tenacity (g/tex)	Elongation (%)
G.12	22.7	4.3	41.8	18.2	$20^s/2$	12.1	13.3	8.0
					20^s	20.1	13.3	8.2
PSH	37.6	3.7	48.8	28.8	$80^s/2$	25.9	23.6	7.5
					80^s	32.3	20.5	5.9

Tensile Properties of Yarns

The relative effects of the treatments are depicted in Figure 1. In the figure, the breadth of the rectangle is proportional to the extension and the height to the tenacity. Even though our study included yarns from different cottons spun to a given count and twist (i.e., same geometry), as well as to different geometries, for the sake of brevity results on just two cottons, each having two different geometries alone, are presented in the figure.

Table II shows data on mechanical properties of two pairs of single and doubled yarns before and after swelling in the two reagents, $ZnCl_2$ and NaOH. Besides the actual values of tensile properties, the percentage changes with respect to the original values are shown in the table. Considerable changes in yarn properties have been brought about by the swelling agents. In case of single yarns (20^s and 80^s), the tenacity was found to decrease by the treatments, while the doubled yarns ($20^s/2$ and $80^s/2$) recorded higher values after the treatment. Extensibility was

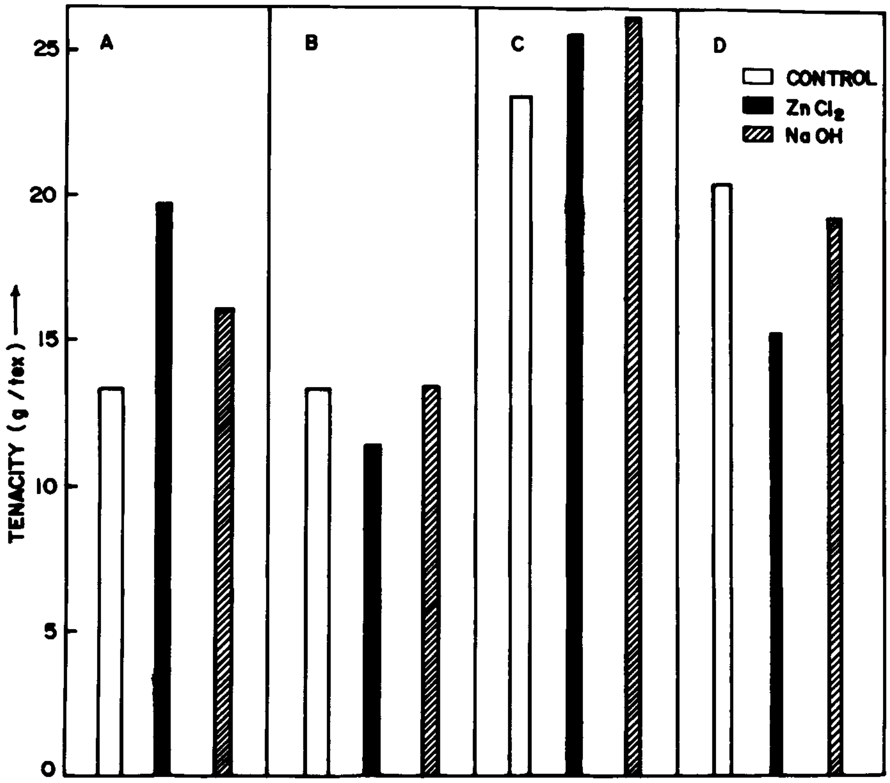

Figure 1 Effect of treatment on yarns of different geometries. A, $20^s/2$; B, 20^s; C, $80^s/2$; D, 80^s. A and B from variety G. 12 and C and D from variety PSH.

Table II Tensile Properties of $ZnCl_2$- and NaOH-Treated Yarns

Count (Ne)	Treatment	Tensile Properties: Tenacity (g/tex)	Elongation (%)	Initial Modulus (g/tex)	Stiffness (g/tex)	% Change: Tenacity	Elongation	Initial Modulus	Stiffness
$20^s/2$	Nil	13.3	8.0	73	166	—	—	—	—
	$ZnCl_2$	19.7	4.3	431	458	48.1	−46.2	490	176
	NaOH	16.1	5.6	118	287	21.1	−30.0	61.6	72.9
20^s	Nil	13.3	8.2	52	162	—	—	—	—
	$ZnCl_2$	11.4	4.9	159	233	−14.3	−40.2	206	43.8
	NaOH	13.4	5.4	115	248	0.8	−34.1	121	53.1
$80^s/2$	Nil	23.6	7.3	192	323	—	—	—	—
	$ZnCl_2$	25.6	4.7	282	545	8.5	−35.6	46.9	68.7
	NaOH	26.2	5.2	298	504	11.0	−28.8	55.2	56.0
80^s	Nil	20.5	5.9	182	347	—	—	—	—
	$ZnCl_2$	15.3	3.3	196	454	−25.4	−44.1	7.7	30.8
	NaOH	19.3	4.2	93	460	−5.8	−28.8	−48.9	32.6

reduced in all four yarns. Values of stiffness and initial modulus were, with the exception of one, higher than those of the untreated yarns. It is also significant to note that the increase in stiffness and modulus was more marked in doubled yarns than in the respective single yarns.

The normalised load-extension graphs for the 20^s and $20^s/2$ yarns are shown in Figure 2. The curves for the single and doubled yarns appear distinctly different. Further, the curve obtained after $ZnCl_2$ treatment is the most steep and linear. As is evident from Table II, this yarn has the maximum percentage increase in the initial modulus.

Yarn and Fiber Orientation

The yarn orientation values ($1/\phi_{1/2}$) measured from the yarn profile are given in Table III, which also shows values of fibrillar orientation of fibers unravelled from the yarns for 20^s and $20^s/2$ for comparison. It may be noted from the table that yarn orientation improves considerably after treatments. However, the values are lower than that for the fibers separated from the yarn.

Packing Fraction of Yarns

Values of packing fraction (PF) for single and doubled yarns both before and after treatments are given in Table IV. In general, PF for the doubled yarn is lower than that for the respective single yarn. Considerable increase in PF is observed after swelling treatments. $ZnCl_2$ brings about much higher increase in PF than NaOH.

The micrographs in Figure 3 clearly show the improvement in packing obtained after swelling and

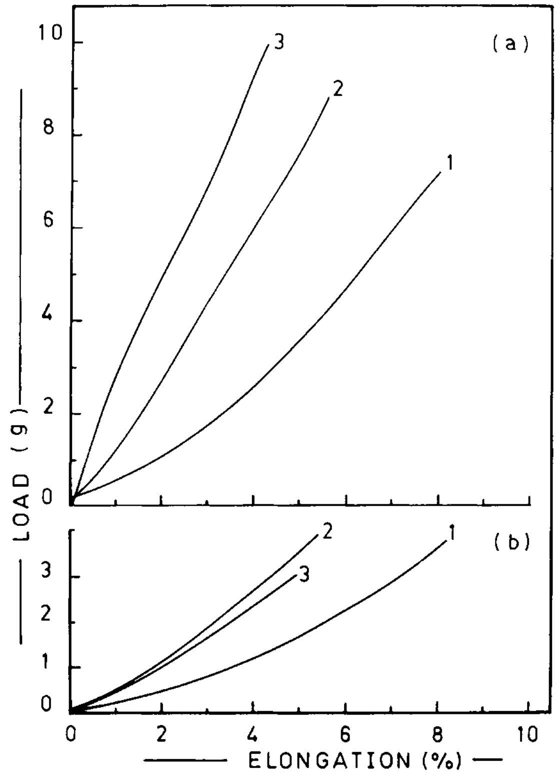

Figure 2 Normalised load-extension curves of control and treated single- and two-ply yarns (a) $20^s/2$, (b) 20^s. 1, control; 2, NaOH; 3, $ZnCl_2$.

Table III X-ray Orientation Values ($1/\phi_{1/2}$) in deg^{-1} for Fibers and Yarns of Various Counts Before and After Treatments

	Fiber[a]		Yarn			
Treatment	$20^s/2$	20^s	$20^s/2$	20^s	$80^s/2$	80^s
Nil	0.0327	0.0327	0.0275	0.0269	0.0324	0.0333
$ZnCl_2$	0.0725	0.0617	0.0556	0.0388	0.0556	0.0529
NaOH	0.0629	0.0546	0.0407	0.0383	0.0498	0.0469

[a] Fibers unravelled from yarns.

stretching. The difference in packing between the control single and doubled yarns is also somewhat obvious from the figure (a, A). This figure not only highlights the less dense packing in the doubled control yarn, but also the ellipticity in its cross-sectional appearance. After $ZnCl_2$ treatment, the doubled yarn cross-section loses its ellipticity and tends to become circular [Fig. 3(B)].

Tenacity and Yarn Orientation

The dependence of tenacity on yarn orientation is shown in Figure 4. It may be noted that when yarns of all geometries are taken together the dependence of tenacity on orientation shows entirely different patterns for single and doubled yarns. Further, neither $20^s/2$ and $80^s/2$ nor 20^s and 80^s fit into a single line, obviously because of the differences in initial tenacities as the yarns originate from widely different varieties of cotton.

Packing Fraction, Tenacity, and Extension

The variation of tenacity with packing fraction is shown in Figure 5. The tenacity–PF relationship also shows countwise segregation. It may be noted that in three out of four cases the tenacity increases initially with increase in packing. However, when PF is substantially high, tenacity shows a drop. The variation in percentage yarn extension with packing is shown in Figure 6. It is significant to note that percentage extension decreases with increase in packing and that a common line could be drawn for all four yarn samples.

Table IV Packing Fraction of Yarns Before and After Treatment

	Count			
Treatment	$20^s/2$	20^s	$80^s/2$	80^s
Nil	0.40	0.46	0.46	0.64
$ZnCl_2$	0.72	0.71	0.69	0.78
NaOH	0.56	0.60	0.62	0.74

DISCUSSION

The foregoing results lead to the following observations:

1. Single and doubled yarns have different tensile behavior, the difference between the two being more spectacular after $ZnCl_2$ treatment.
2. Chemical treatments improve fiber packing in yarns of all geometries, unlike tenacity, which may increase or decrease.
3. Orientational changes are somewhat similar in yarns of all geometries, although the improvement is maximum after treatment in $ZnCl_2$.

The tenacity of a yarn is basically decided by the inherent strength of fiber elements constituting the yarn. However, when the tenacity of yarns spun from the same variety of cotton differs as between 80^s and $80^s/2$ or 20^s and $20^s/2$, the difference has to be traced to other factors like the alignment of the fibers and their packing in the yarn body.

The orientation measured with fibers unravelled from yarns gives the orientation of molecular assemblies (fibrils) with respect to the fiber axis. On the other hand, orientation measured from the yarn profile would reflect geometrical effect because the surface twist angle would be different for yarns of different counts. This is the basic reason why yarn orientation measurement is preferable to fiber orientation when the influence of orientation on yarn tenacity is considered.

There is remarkable increase in orientation (Table III) after swelling and stretching treatments, the

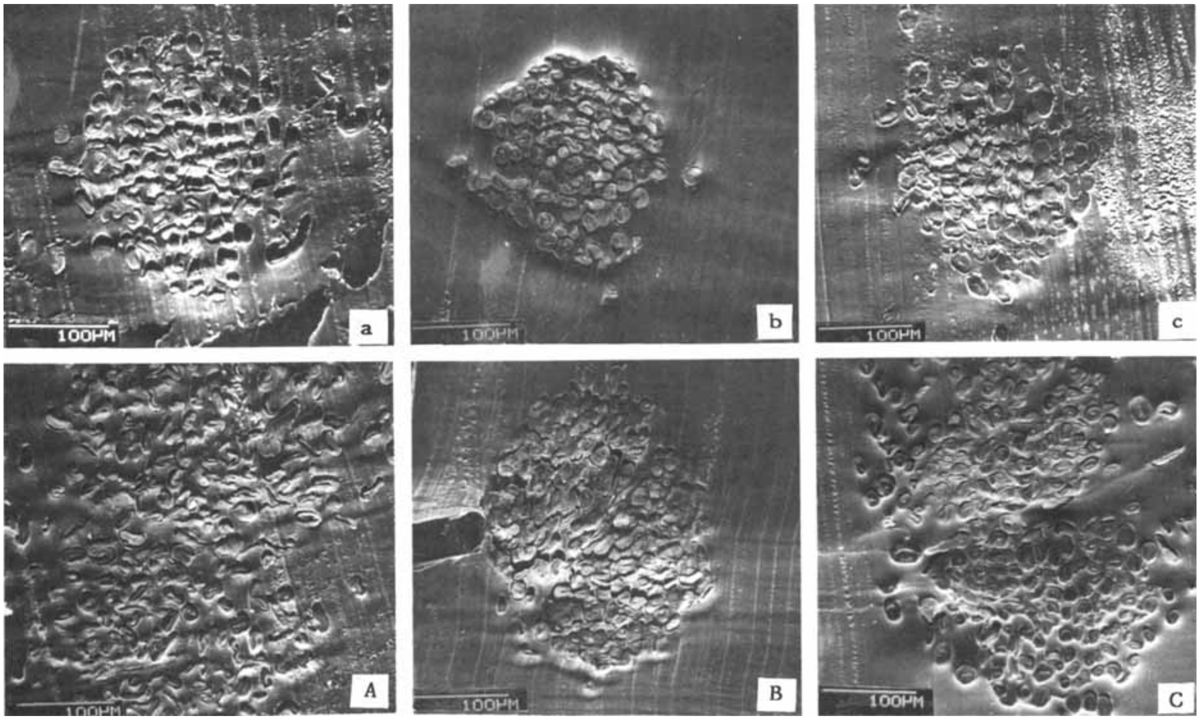

Figure 3 Photomicrographs of cross-sections of two-ply and single yarns. (A, a), control, (B, b), $ZnCl_2$ treated; (C, c), NaOH treated.

increase being the highest for doubled yarns of lower count ($20^s/2$) treated in $ZnCl_2$. This yarn initially had the lowest PF value (Table IV), which suggests a relatively loose packing for the fiber elements in the yarn. This would help a better and more uniform swelling during treatments and lead to marked increase in orientation during subsequent stretching. This is true in the case of $80^s/2$ yarn also and both $20^s/2$ and $80^s/2$ yarns show increase in tenacity that go hand in hand with orientation. However, the corresponding single yarns (20^s and 80^s) show a decrease in tenacity in spite of orientational improvement. In other words, yarns may differ in tenacity even when spun from the same fibers, where all factors contributing to yarn tenacity like fiber strength, fiber length, and fiber fineness remain the same and orientation is not much different (as in the case of 80^s and $80^s/2$ or 20^s and $20^s/2$). This difference in tenacity among yarns should now be traced to changes in other parameters like packing fraction produced by the treatments.

The increase in compactness is also brought out by the cross-sections of yarns shown in Figure 3. The compactness is the maximum after swelling and stretching in $ZnCl_2$. This indicates the profound influence of the bivalent Zn^{++} ion, which converts the assembly of fibers into some sort of a gel during swelling. The excessive swelling helps to get the fibers oriented to a very high level during subsequent stretching.

Actual packing of the fiber elements in the body of the yarn measured by the index PF gets considerably altered by the treatments (Table IV). It is but natural that swelling accompanied by stretch to original length brings the fibers closer to one another in the yarn, thereby making it more compact while at the same time leaving the tpi and yarn count largely unchanged. The chemical treatment thus serves to increase the orientation of fibrils in the fibers and the compactness of the fibers in the yarn without changing the tpi and count.

A close parallel may be drawn between the packing fraction–tenacity relation in the treated yarn shown in Figure 5 of the present work and the well-known twist–tenacity relation in the raw yarn.[4–7] It appears that there exists a state of "ideal packing" that would offer interfiber friction favourable for good strength realisation. When packing exceeds this ideal value, interfiber friction becomes too high to allow fiber realignments necessary for maximum

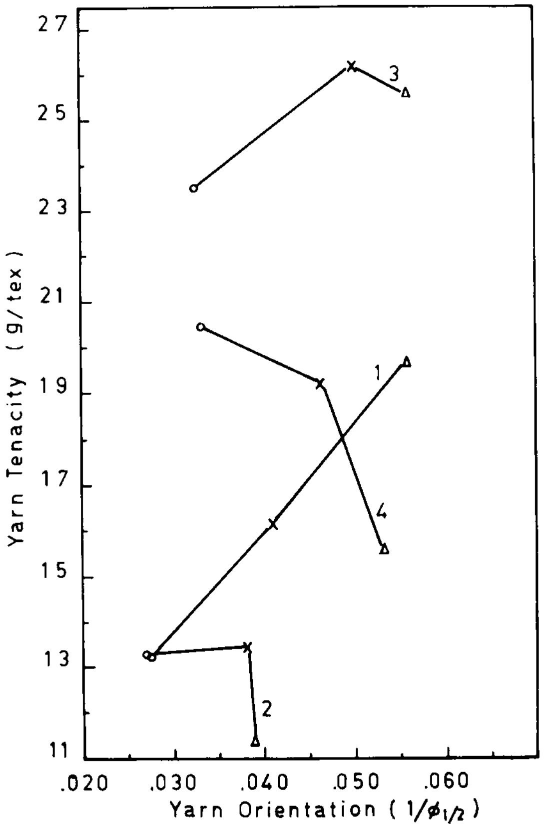

Figure 4 Dependence of yarn tenacity on orientation ($1/\phi_{1/2}$). 1, 20^s/2; 2, 20^s; 3, 80^s/2; 4, 80^s. O, control; Δ, $ZnCl_2$; ×, NaOH.

strength realisation and the tenacity falls. This is also substantiated by the decrease in yarn elongation with increase in packing (Fig. 6) where all yarns have received the same stretch. Elongation is well correlated with packing ($r = -0.88$) and no countwise segregation is observed because stretching produces only decrease in elongation of the yarns irrespective of count, unlike tenacity, which can show either increase or decrease as decided by other factors like orientation.

The ideal PF value for the highest tenacity realisation does not seem to depend much on yarn count. A value of PF in the vicinity of 0.65 seems to produce maximum improvement in tenacity for a given orientation. The 20^s/2 yarn, which attains a PF of 0.72 after $ZnCl_2$ treatment, would have shown a drop in tenacity but for the very high orientation reached during stretching. Even though the 20^s yarn too attained nearly the same PF (0.71) after treatment, its tenacity showed a decrease because of poorer ori-

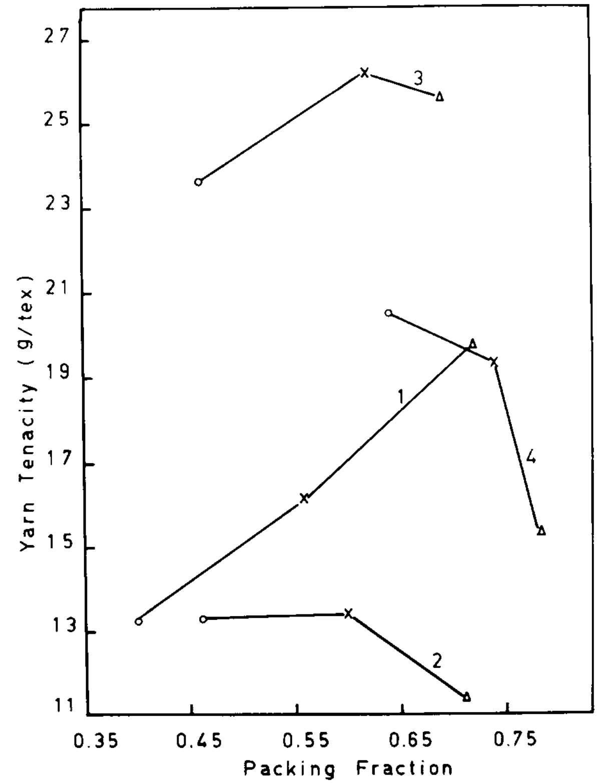

Figure 5 Dependence of yarn tenacity on packing fraction (PF). 1, 20^s/2; 2, 20^s; 3, 80^s/2; 4, 80^s. O, control, Δ; $ZnCl_2$; ×, NaOH.

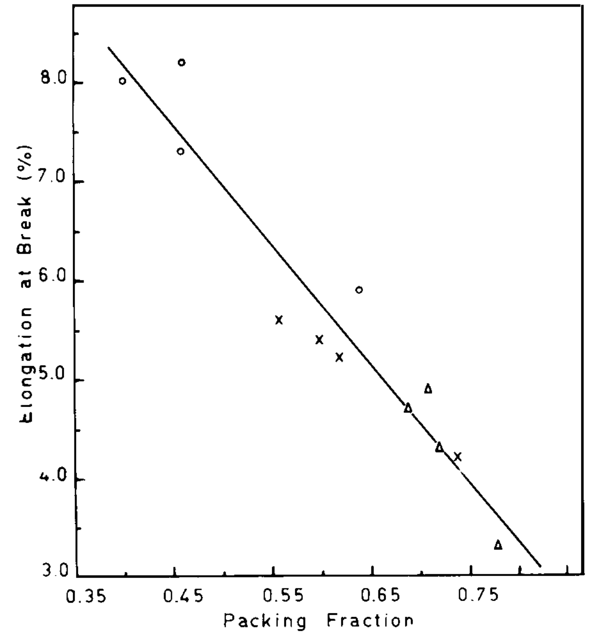

Figure 6 Relationship between breaking elongation (E%) and packing fraction (PF). O, control; Δ, $ZnCl_2$; ×, NaOH.

entation (0.0388 in place of 0.0556 for $20^s/2$). The earlier study on fibers[1] treated in $ZnCl_2$ had shown that in spite of considerable improvement in orientation the percentage increase in tenacity in fine cotton is far less than that in coarse cottons. The marginal improvement in tenacity for the $80^s/2$ yarn in spite of considerable improvement in orientation (which is almost the same as that for $20^s/2$) and PF being only marginally different from the ideal value may be due to the minimum role played by orientation in improving the tenacity of these yarns. The 80^s yarn treated in $ZnCl_2$ shows nearly the same orientation (0.053) as $80^s/2$ (0.055), but its PF (0.78) is much higher. This sample suffers a substantial drop (25.4%) in tenacity in spite of the orientational improvement. The negative role played by packing has more than offset the effect from the orientational improvement.

There is also the possibility that the excessive swelling pressure exerted by the Zn^{++} ion during swelling may lead to fusing of a few adjacent fibers, more likely in the case of a yarn that has a higher packing even before swelling. The 80^s yarn had a PF of 0.62 initially and had shown signs of random fusion that might have occurred during swelling and stretching. Slippage of elements would become much more difficult and the yarns would break at a lower extension and load than otherwise. This yarn had registered the lowest percentage extension.

In the case of NaOH-treated samples, both doubled yarns ($20^s/2$ and $80^s/2$) showed improvement in tenacity that can be easily related to orientational and PF improvements. Despite a near optimum packing (0.60), the 20^s single yarn did not show any significant improvement in tenacity, probably because increase in orientation is only marginal. In the case of 80^s single yarn, there is a decrease in tenacity after treatment, probably because of relatively higher packing. Further, this yarn was spun from a finer cotton, and the orientation could not help much in increasing tenacity as already noted. However, the decrease is not as conspicuous as that in the 80^s yarn treated in $ZnCl_2$. In other words, the effect produced by the action of bivalent Zn^{++} ion on the single yarn that had a high PF to begin with is much more drastic and detrimental to yarn strength than that produced by the monovalent alkali ion.

CONCLUSIONS

When yarns of different geometries spun from the same fibers differ in tensile behaviour, the differences have to be traced to factors like orientation and packing of the fibers in the yarn. Orientational improvement produced by swelling treatment always helps to increase tenacity, the exact magnitude being decided by the variety of cotton. The role played by increase in packing can be positive, zero, or negative depending on the actual value resulting from the treatment. Swelling treatments increase the compactness of the fibers in the yarns without changing the yarn count and tpi. Two-ply yarns spun from short staple cottons seem to be ideal for chemical treatments than single yarn spun from more uniform long staple varieties. When the packing in the yarn prior to treatment is closer to the "ideal packing," swelling and stretching helps little to improve the tenacity. On the contrary, the treatment may be even detrimental to yarn strength.

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