Effect of Single Yarn Twist and Ply to Single Yarn Twist Ratio on Strength and Elongation of Ply Yarns

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ABSTRACT: The amount of ply twist required to bring the surface fibers of the strand parallel to ply yarn axis is half the single yarn twist and, is experimentally verified by viewing the multifilament yarns longitudinally under Scanning Electron Microscope. The effect of single yarn twist and ply to single yarn twist ratio on strength and elongation of two-ply cotton yarn have been studied. As the single yarn twist increases the tensile strength of the ply yarns with different levels of ply to single yarn twist ratio increases and at 130–140% of normal single yarn twist level, the ply yarns attain almost the same strength. Rate of improvement in tensile strength of cotton two-ply yarn with respect to single yarn twist is more than that with respect to ply twist. The effect of ply to single yarn and cable to ply yarn twist ratio on strength and elongation of ply and cable multifilament yarns have been studied. Tensile strength of ply and cable multifilament yarns do not vary with the change in ratio of ply to single yarn twist and cable to ply twist respectively, particularly when the resultant yarn is finer. The cosine of average filament inclination to the ply yarn axis and that to the cable yarn axis do not vary much with different levels of ply to single yarn twist ratio and cable to ply yarn twist ratio respectively. J Appl Polym Sci 98: 2245–2252, 2005

Key words: strength; elongation; fiber-to-fiber cohesion; ply twist; yarn helical angle

INTRODUCTION

Yarn is an assembly of staple fibers or filaments produced by spinning. Not all yarns resulting from staple-fiber spinning have properties that satisfy all the requirements of their various applications. A subsequent process of post-twisting is therefore sometimes applied, to improve their properties. Plying improves abrasion resistance, strength, elongation, evenness, luster, and bulkiness and reduces hairiness, twist liveliness, and variation in strength.[1–3] Staple yarn is normally ply twisted in the direction opposite to single yarn twist. It is interesting to note that the yarn structure produced during spinning is entirely changed during plying. The structure of ply yarn, which can be expressed in terms of ply twist angle and the angle of the fibers in the strand to the ply yarn axis, mainly depends on level of single yarn twist and ply yarn twist. Hence it is required to study the effect of single yarn twist and ply yarn twist on the structure and properties of ply yarn.

In this study, the ratio of ply to single yarn twist required to bring the surface fibers of the strand parallel to the ply yarn axis and the effect of ply to single yarn twist ratio and cable to ply twist ratio on strength and elongation of two-ply and cable yarns have been studied.

Strength of ply yarn

The spun yarn strength mainly depends on fiber orientation and fiber-to-fiber cohesion. To get maximum possible yarn tenacity, maximum orientation and optimum fiber cohesion are required. Once the single yarn is twisted to impart cohesion between the fibers, the fibers will no longer be parallel to the yarn axis. But the above said condition, i.e., maximum orientation and optimum cohesion, can be more or less reached in a two-ply yarn structure. It is possible to arrange fibers in a particular layer exactly parallel to the ply yarn axis with fibers in the other layers arranged slightly inclined to the ply yarn axis. For example, if the fibers in the middle layer of the strand are kept parallel to the ply yarn axis, then fibers on either side of the middle layer are arranged at a smaller inclination to the ply yarn axis depending upon the distance of the layer from the middle layer. But the average inclination of fibers to the axis of the ply yarn will be smaller compared with that of single yarn.

In general, it can also be inferred that to arrange fibers in a particular layer of strand parallel to ply yarn axis, ply twist angle should be equal to twist angle of that particular layer of fibers in the strand.

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TABLE I
Specifications of Nylon Sewing Threads and Fish Net Twines

Material	Denier/ply/cable	No. of filaments in single yarn	Single yarn twist (turns/cm)	Ply twist (turns/cm)	Cable twist (turns/cm)
Sewing threads	210/2	24	8.03	5.53	—
	890/2	72	4.23	2.70	—
Fishnet twines	210/2/2	24	0.10	4.90	3.23
	210/2/3	24	0.10	5.91	3.15
	210/3/3	24	0.10	4.45	3.10
	210/4/3	24	0.10	5.47	2.80
	210/5/3	24	0.10	5.42	2.55
	210/6/3	24	0.10	5.10	2.49
	210/7/3	24	0.10	5.27	2.41
	210/8/3	24	0.10	4.72	2.20
	210/9/3	24	0.10	4.26	1.97
	210/10/3	24	0.10	4.07	1.84

It may be noted that the terms 'single yarn' and 'strand' refer to single yarn before plying and single yarn present in the ply yarn respectively. The direction of ply twist is always opposite to the direction of single yarn twist unless otherwise stated.

Ratio of ply to single yarn twist required to bring surface fibers of the strand parallel to two-ply yarn axis

The ply and the strand twist angles can be calculated assuming the yarn is of an idealized helical structure.[4]

$$\tan \alpha_3 = 2\pi r N_3 \quad (1)$$

$$\tan\alpha_2 = 2\pi r N_2 \quad (2)$$

where α_3 is the angle of axis of the strand to the ply axis, α_2 is the angle of surface fibers to the strand axis, r is the radius of the single yarn (cm), N_3 is the ply twist (turns/cm), N_2 is the single yarn twist after plying, i.e., strand twist (turns/cm), N_1 is the single yarn twist before plying.

To arrange surface fibers parallel to ply yarn axis, ply twist angle α_3 should be equal to strand twist angle α_2. Equating the eqs. (1) and (2) as per the above condition yields

$$N_2 = N_3 \quad (3)$$

It means that to bring the surface fibers parallel to the ply axis, the ply twist should be equal to strand twist. Schwarz[5] derived a relationship between single yarn twist, ply twist, and strand twist.

$$N_2 = N_1 - N_3 \cos^2\alpha_3 \quad (4)$$

Assuming $\cos^2 \alpha_3 = 1$ and substituting eq. (3) in the eq. (4), the eq. (4) becomes:

$$N_3 = N_1/2 \quad (5)$$

The amount of ply twist required to bring the surface fibers parallel to ply yarn axis is half the single yarn twist. This ratio is same as that of Woods's[6] and Treloar's[7] prediction to bring the surface filaments parallel to ply yarn axis.

By assuming the strands in the three-ply yarn are circular in crosssection and the three circles are touching each other and they follow a helical path, the ply to single yarn twist ratio required to bring the surface fibers of the strands parallel to three-ply yarn axis was calculated in a similar manner as explained above for two-ply yarn, and it is found to be 0.4641.

METHODS

Preparation of yarn samples

Combed cotton yarns of 14.8 tex, 11.8 tex, and 9.8 tex were spun using a Lakshmi G 5/1 Ring frame from the roving of 369.1 tex, 281.2 tex, and 246 tex respectively. The yarn samples were produced with different levels of twist in Z direction with the twist level varying from normal level to 50% higher than the normal twist level. Subsequently each of these yarn samples was ply twisted in the direction opposite to single yarn twist at three different ply twist levels (1/3, 1/2, and 3/4 the single yarn twist).

Testing of yarn samples

The tensile strength and elongation of two-ply cotton yarns were measured using a Premier Tensomaxx tensile tester with a gauge length of 500 mm, pretension of 0.05 cN/tex and testing speed of 5000 mm/min. Average tensile strength and elongation were calculated after testing three cops per sample with 30 tests in each cop.

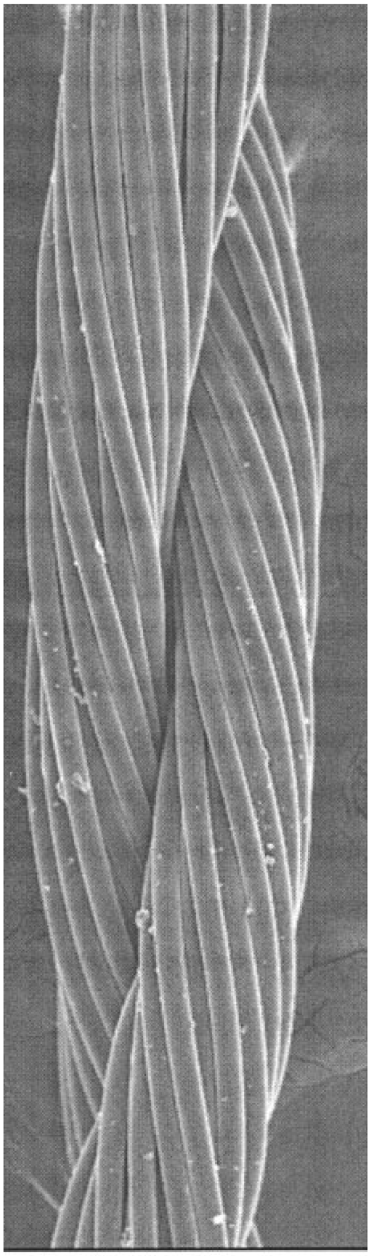


Figure 1 SEM photograph of two-ply 210/2-denier multifilament yarn with 1/3 the single yarn twist as ply twist. Magnification: ×50.

Nylon sewing thread and nylon fish net twines were procured from the manufacturer and their particulars are given in Table I. Ply and cable yarn twist levels were altered using twist tester to get ply to single yarn twist and cable to ply twist of 1/3, 1/2, and 3/4 the single and ply yarn twist respectively. The tensile strength and elongation of the yarns with the altered twist levels were measured in an Instron tensile tester as per ASTM 2256−02 Standard for all the yarn samples. The SEM photographs were taken for 210/2 denier ply yarn with the altered twist levels.

Calculation of average filament angle to the ply axis

To calculate the average filament angle with respect to ply axis, it is assumed that the filaments in the yarn are ideally open packed.[4]

The radius of the filament can be calculated by the expression:

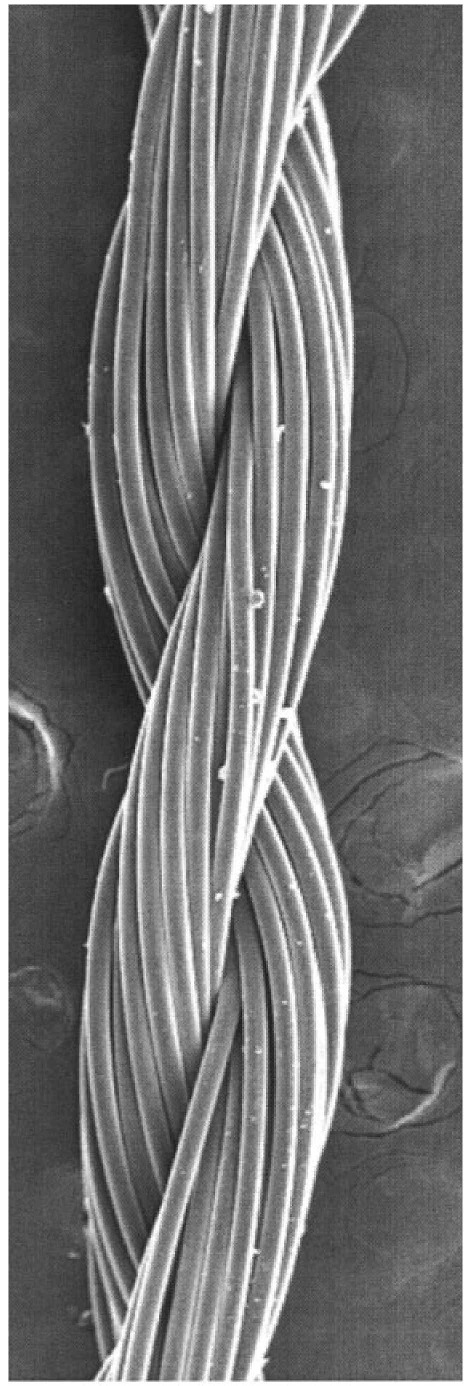
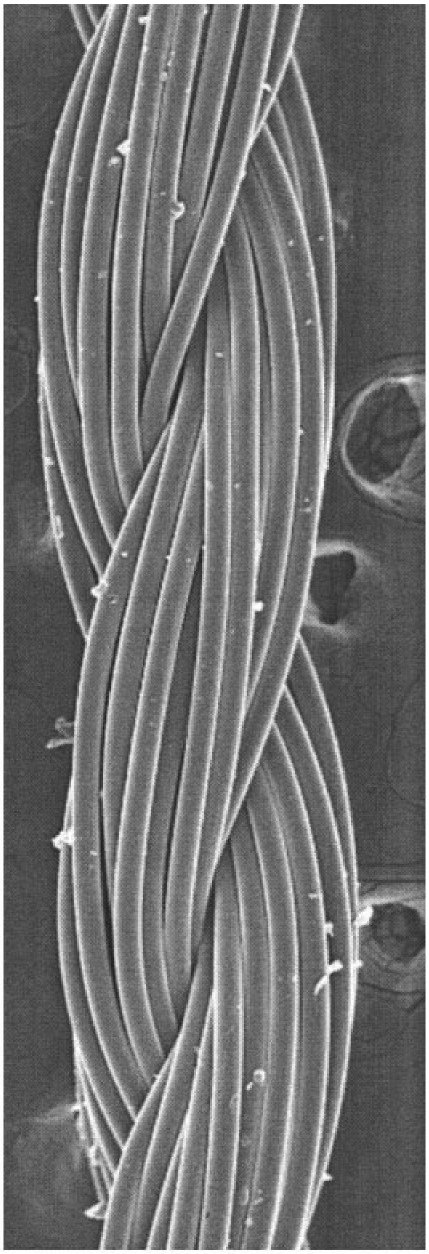


Figure 2 SEM photograph of two-ply 210/2-denier multifilament yarn with 1/2 the single yarn twist as ply twist showing the surface filaments parallel to ply yarn axis. Magnification: ×40.



Magnification: X50

Figure 3 SEM photograph of two-ply 210/2-denier multifilament yarn with 3/4 the single yarn twist as ply twist. Magnification: ×50.

$$r_f = \sqrt{\frac{D}{9\pi 10^5 \rho}} \tag{6}$$

where r_f is the radius of filament (cm), D is the denier of filament, ρ is the density of filament (g/cm^3).

The distance of the center of any layer from the axis of the single yarn is

$$X = 2(n-1)r_f \tag{7}$$

where n is the layer number.

The helical angle of the filaments in any particular layer can be expressed as

$$\tan\alpha = 4\pi(n-1)r_f N_2 \tag{8}$$

where N_2 is the strand twist (turns/cm).
The angle of fibers with respect to ply yarn axis will be the difference between the ply twist angle and helical angle of filaments with respect to the strand axis. By calculating the filament angle with respect to ply yarn axis for all the layers, the average filament angle to the ply axis can be calculated.

Average filament angle to the ply axis was calculated as explained above for all the multifilament sewing threads and fish net twines. For the calculation of average filament angle, the cable-twisted fish net twines were considered as ply yarns for the following reason. Nylon fish net twines were produced by cabling two or three ply yarns in *Z* direction. The ply yarns had been earlier produced by combining the required number of basic yarns and twisting them together in *S* direction. During plying operation, small amount of producer twist present in the basic yarn (0.1 turns/cm in *Z* direction) is removed and all the yarns are now integrated into a yarn which would be more like a single multifilament yarn.[8]

RESULTS AND DISCUSSION

Effect of ply to single yarn twist ratio on filament angle with respect to ply yarn axis

The amount of ply twist required to bring the surface fibers parallel to the ply yarn axis is derived and found to be half the single yarn twist (eq. 5). To verify experimentally the above prediction, multifilament two-ply 210/2 denier yarns were viewed longitudinally under Scanning Electron Microscope (SEM) and photographs were taken. The longitudinal views of two-ply yarns are shown in Figures 1–3. The filaments on the surface of two-ply yarn with 1/2 the single yarn twist are more or less parallel to the ply axis, whereas the filaments on the surface of two-ply yarns with 1/3 and 3/4 the single yarn twist are arranged at a certain angle in *S* and *Z* direction to the ply yarn axis respectively. The above observations conform to the prediction made from the equation.

Effect of ply to single and cable to ply yarn twist ratio on tensile strength and elongation of multifilament ply and cable yarns

Studies were conducted on multifilament ply and cable yarn strength by varying the ply to single yarn twist ratio and cable to ply twist ratio respectively.

Table II shows the tensile strength and elongation of two-ply and cable multifilament yarns. It is interesting to note that the tensile strength of two-ply filament

TABLE II
Effects of Ply to Single and Cable to Ply Yarn Twist Ratio on Strength and Breaking Elongation of Multi Filament Ply and Cable Yarns

	Ply/cable yarn with 1/3 the single/the ply yarn twist				Ply/cable yarn with 1/2 the single/the ply yarn twist				Ply/cable yarn with 3/4 the single/the ply yarn twist			
Denier/ply/cable	Strength (kgs)	Average filament angle α (degrees)	cos α	Breaking elongation (%)	Strength (kgs)	Average filament angle α (degrees)	cos α	Breaking elongation (%)	Strength (kgs)	Average filament angle α (degrees)	cos α	Breaking elongation (%)
210/2/2	4.88	3.57	0.9980	16.6	4.89	5.17	0.9959	16.4	4.99	15.03	0.9658	17.5
210/2/3	8.62	3.91	0.9977	21.1	8.58	8.40	0.9893	23.0	8.57	18.46	0.9485	26.2
210/3/3	12.06	3.81	0.9978	19.2	12.18	5.73	0.9950	20.0	12.08	14.75	0.9670	22.0
210/4/3	15.72	5.56	0.9953	22.3	15.53	5.56	0.9953	23.8	14.99	19.04	0.9453	31.0
210/5/3	19.45	6.00	0.9945	25.1	19.23	6.93	0.9926	27.0	18.58	22.01	0.9271	38.7
210/6/3	23.14	5.82	0.9948	25.2	22.91	8.11	0.9900	27.6	22.27	23.83	0.9147	40.0
210/7/3	27.00	6.80	0.9929	28.1	27.39	7.51	0.9914	30.0	25.45	23.91	0.9142	47.8
210/8/3	30.33	6.26	0.9940	25.9	30.39	8.19	0.9898	28.5	28.72	24.58	0.9094	44.0
210/9/3	35.28	6.34	0.9939	26.3	35.13	6.81	0.9929	28.8	33.48	22.34	0.9249	42.7
210/10/3	38.15	6.03	0.9945	28.5	37.95	7.96	0.9904	30.2	35.94	23.91	0.9142	45.2
210/2	2.68	4.56	0.9968	29.9	2.67	5.17	0.9959	27.9	2.64	13.30	0.9732	30.3
890/2	3.74	4.24	0.9973	30.4	3.76	6.40	0.9938	31.1	3.76	18.09	0.9506	33.1

yarns does not vary significantly with the amount of ply twist.

While the staple fiber ply yarn strength depends on fiber-to-fiber cohesion and fiber orientation, the multifilament ply yarn strength mainly depends on fiber orientation. To find out the effect of fiber orientation, the cosine of average filament angle was calculated, as this would reflect the contribution of filaments to withstand the applied axial load. The average filament angle to the ply yarn axis was calculated and given in Table II. The difference in cosine of average filament angle to the ply axis between multifilament two-ply yarns with 1/3, 1/2, and 3/4 the single yarn twist is found to be less than 5% and hence the effect of fiber orientation on ply yarn strength is insignificant for the range of ply twist used.

Table II shows that at a lower level of ply (up to 9 ply), there is insignificant difference in tensile strength

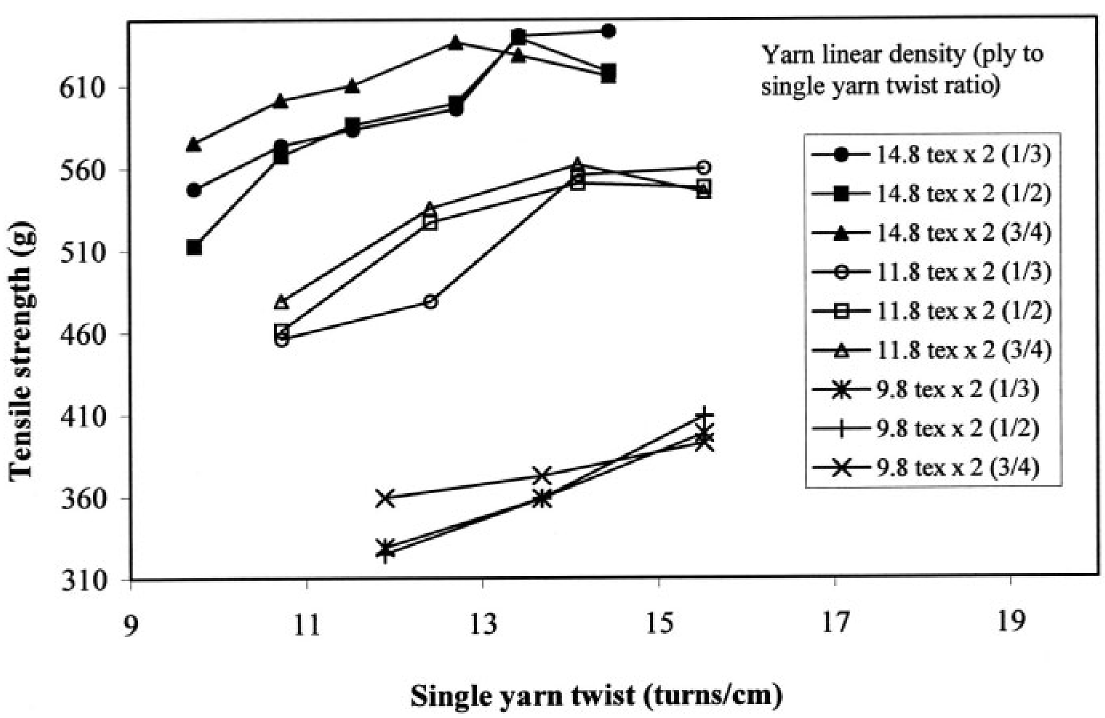


Figure 4 Effect of single yarn twist on tensile strength of 14.8 tex × 2, 11.8 tex × 2, and 9.8 tex × 2 cotton ply yarns.

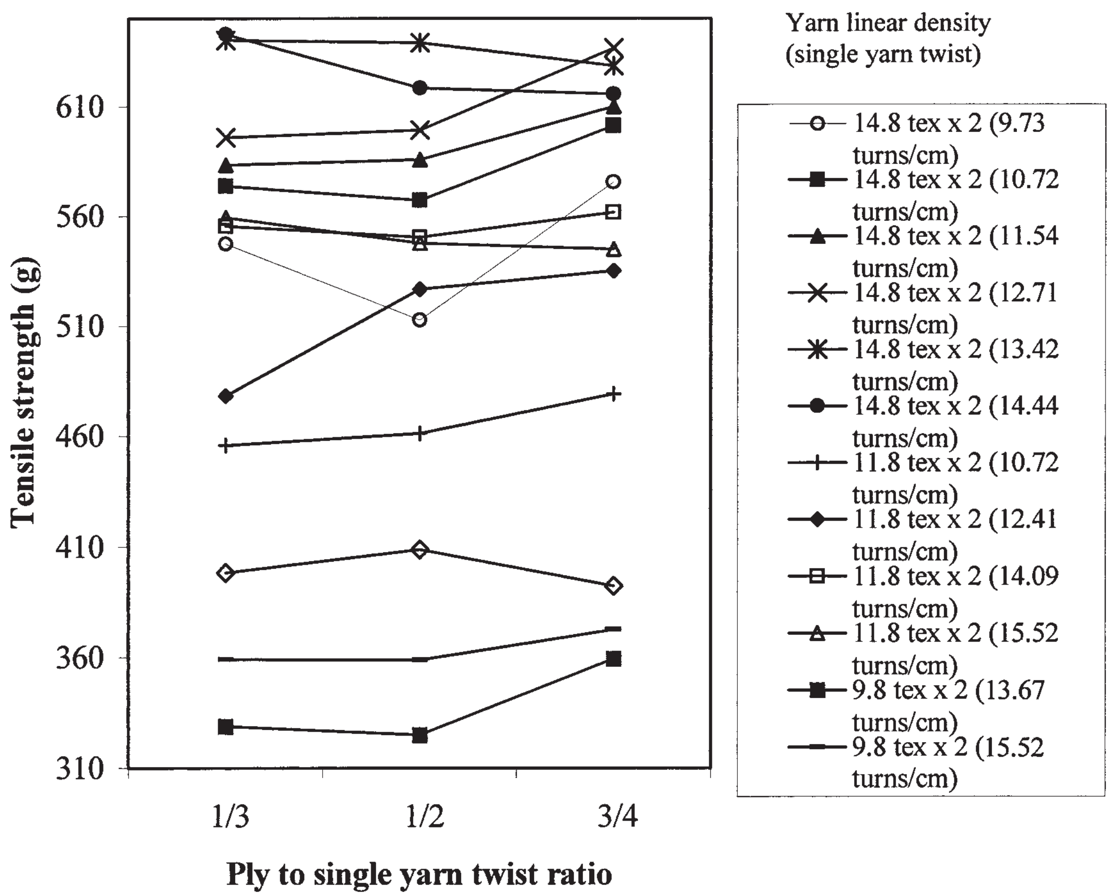


Figure 5 Effect of ply to single yarn twist ratio on tensile strength of 14.8 tex × 2, 11.8 tex × 2, and 9.8 tex × 2 cotton ply yarns.

between the cable yarns with 1/3, 1/2, and 3/4 the ply twist as in the case of ply yarn. The maximum difference in the cosine of average filament angle is about 3% only. However, as number of ply increases above nine, the difference in tensile strength between the cable yarns with 1/3, 1/2, and 3/4 the ply twist increases. The cable yarn with 1/3 the ply twist level shows highest tensile strength followed by cable yarns with 1/2 and 3/4 the ply twist. A careful observation of Table II will allow to infer that the above trend can be attributed to cosine of average filament angle. While the maximum difference in tensile strength between cable yarns with different amount of cable twist is about 6%, the maximum difference in cosine of average filament angle is about 8%.

From the above discussion, it can be concluded that with in the above range of ply and cable twist, the filament orientation to the yarn axis does not significantly influence the ply and cable yarn strength and more so particularly in case of finer yarn.

The breaking elongation is higher for the ply and cable yarns with 3/4 the single yarn twist and ply twist respectively, than the ply and cable yarns with 1/3 and 1/2 the single and ply twist. This may be due to the higher amount of wrapping of one strand over another obtained through higher ply and cable twist.

TABLE III
Percentage Improvement in Tensile Strength of Two-Ply Yarns per Turn of Single Yarn Twist

Yarn linear density	Average % improvement in tensile strength of two-ply yarns per turn of single yarn twist			
	At ply twist of 1/3 the single yarn twist	At ply twist of 1/2 the single yarn twist	At ply twist of 3/4 the single yarn twist	Grand average
14.8 tex × 2	1.3	1.3	0.57	1.06
11.8 tex × 2	1.8	1.5	1.1	1.47
9.8 tex × 2	2.2	2.7	1.0	1.97

TABLE IV
Percentage Improvement in Tensile Strength of Two-Ply Yarns per Turn of Ply Twist

	Average % improvement in tensile strength of two-ply yarns per turn of ply twist	
Yarn linear density	When the ply twist is increased from 1/3 to 1/2 the single yarn twist	When the ply twist is increased from 1/2 to 3/4 the single yarn twist
14.8 tex × 2	−0.23	0.48
11.8 tex × 2	0.03	0.50
9.8 tex × 2	0.06	0.48

Effect of single yarn twist and ply to single yarn twist ratio on tensile strength and elongation of two-ply cotton yarn

Figure 4 shows the tensile strength of 14.8 tex ×2, 11.8 tex ×2, and 9.8 tex ×2 two-ply cotton yarns. At the normal single yarn twist level, the two-ply yarn with 3/4 the single yarn twist shows highest tensile strength, in spite of the fact that 3/4 the single yarn twist in each strand in the ply yarn is removed during plying. From the studies conducted on filament yarns, it was found that the fiber orientation does not significantly affect ply yarn strength for the range of ply twist used. So it can be inferred that the cotton two-ply yarn strength would mainly depend on fiber-to-fiber cohesion. The higher strength for the two-ply yarn with 3/4 the single yarn twist may be due to better cohesion and better utilization of ineffective layer of the fibers obtained through more wrapping of one strand over another. With high pressure applied on the surface of each strand due to high ply twist, the ply yarns utilize the strength contribution of the ineffective layer of fibers trapped between the strands.[1] Since the two-ply yarn with 1/3 and 1/2 the single yarn twist has neither enough strand twist nor ply twist to impart cohesion between the fibers and also to make the ineffective layer to contribute to the yarn strength, they exhibit lower strength.

As the single yarn twist increases, the amount of ply twist, strand twist, and frequency of surface fiber trapping between the strands in the ply yarn increases and hence the tensile strength of the ply yarn increases and the difference in tensile strength between the yarns with 1/3, 1/2, and 3/4 single yarn twist becomes narrower. These ply yarns attain almost same strength level at around single yarn twist of 130–140% of normal single yarn twist level. Further increase of single yarn twist does not increase the tensile strength of the yarn, rather it decreases. While the increase in fiber-to-fiber cohesion improves the yarn strength, the increase in fiber obliquity to ply yarn axis would cause reduction in strength when the single yarn twist is increased. Once the maximum cohesion between the fibers is achieved, further increase of twist will cause reduction in yarn strength due to greater fiber obliquity.

The results obtained from the studies on both filament and staple fiber yarns reveal that high ply twist can be given to staple fiber yarn to obtain high strength as the change of fiber orientation by the change of ply twist does not significantly influence ply yarn strength. For producing high strength cotton ply yarns, it is advisable to produce the single yarn with twist 10–20% higher than the normal twist level and ply twist the yarn with 3/4 the single yarn twist.

Figure 5 shows the effect of ply to single yarn twist ratio on tensile strength of 14.8 tex ×2, 11.8 tex ×2, and 9.8 tex ×2 cotton two-ply yarns. Generally, there is no significant change in the ply yarn strength when the ply twist is increased from 1/3 to 1/2 the single yarn twist. At low level of single yarn twist (up to 130% of single yarn twist), increasing the ply to single yarn twist ratio from 1/2 to 3/4 increases the ply yarn strength. However at high single yarn twist level,

TABLE V
Effect of Single Yarn Twist and Ply to Single Yarn Twist Ratio on Breaking Elongation of 14.8 tex × 2, 11.8 tex × 2, and 9.8 tex × 2 cotton ply yarns

Ply to single yarn twist ratio	Single yarn twist (turns/cm)												
	9.73	10.72	11.54	12.71	13.42	14.44	10.72	12.41	14.09	15.52	11.89	13.67	15.52
	Breaking elongation of 14.8 tex × 2 cotton ply yarn						Breaking elongation of 11.8 tex × 2 cotton ply yarn				Breaking elongation of 9.8 tex × 2 cotton ply yarn		
1/3	4.9	5.3	5.4	5.7	6.4	6.7	4.9	5.3	5.4	5.7	5.0	5.5	5.8
1/2	5.1	5.2	5.2	5.6	6.1	6.1	5.1	5.2	5.2	5.6	5.4	5.6	5.5
3/4	5.3	6.1	6.4	6.7	6.9	6.6	5.3	6.1	6.4	6.7	5.8	6.3	6.6

increasing the ply to single yarn twist ratio from 1/2 to 3/4 reduces the ply yarn strength.

Tables III and IV show percentage improvement in tensile strength due to increase of one turn of single yarn twist and ply twist respectively. These results reveal that single yarn twist has a more influential effect than the ply twist on tensile strength of ply yarn.

Table V shows the effect of single yarn twist and ply to single yarn twist ratio on breaking elongation of 14.8 tex $\times$2, 11.8 tex $\times$2, and 9.8 tex $\times$2 cotton two-ply yarns. The table shows that in general the two-ply yarn with 3/4 the single yarn twist has higher breaking elongation percentage than two-ply yarns with 1/3 and 1/2 the single yarn twist. This may be due to higher amount of wrapping of one strand over another for the two-ply yarns with 3/4 the single yarn twist than for the other two yarns.

At low level of single yarn twist, increasing the ply to single yarn twist ratio from 1/3 to 1/2 increases the elongation of ply yarn to a small extent. However at high single yarn twist level, increasing the ply to single yarn twist ratio from 1/3 to 1/2 reduces the elongation of ply yarn. Increasing the ply to single yarn twist ratio from 1/2 to 3/4 increases the elongation of ply yarns irrespective of single yarn twist levels.

As the single yarn twist increases, the breaking elongation of the two-ply yarns increases irrespective of count and ply twist level because of the increase in strand twist and ply twist.

CONCLUSIONS

i) To arrange fibers in a particular layer of the strand parallel to ply yarn axis, ply twist angle should be equal to twist angle of that particular layer of fibers.

ii) The filaments on the surface of two-ply yarns with 1/2 the single yarn twist are arranged more or less parallel to the ply yarn axis whereas, the filaments on the surface of two-ply yarns with 1/3 and 3/4 of single yarn twist are arranged at a smaller inclination in the direction of single yarn twist and ply twist respectively, to the ply yarn axis. The above experimental observation made using SEM proves the theoretical prediction that the ply twist required to bring the surface fibers parallel to the ply yarn axis is half the single yarn twist.

iii) Tensile strength of two-ply and cable multifilament yarns does not vary with the change in amount of ply and cable twist studied respectively, at low linear density level.

iv) The breaking elongation is higher for the ply and the cable yarns with 3/4 the single yarn twist than those with 1/3 and 1/2 the single yarn and ply twist.

v) Rate of improvement in tensile strength of cotton two-ply yarn with respect to twist is more for the single yarn twist than for the ply twist.

vi) At the normal single yarn twist level, the two-ply yarn with 3/4 the single yarn twist shows higher tensile strength than two-ply yarns with 1/3 and 1/2 the single yarn twist.

vii) For the staple fiber yarn, as the single yarn twist increases up to 130–140% of normal single yarn twist, the two-ply yarns strength increases and the difference in tensile strength between the yarns with 1/3, 1/2, and 3/4 the single yarn twist decreases.

viii) For producing high strength cotton ply yarns, it is advisable to produce the single yarn with twist 10–20% higher than the normal twist level and ply twist the yarn with 3/4 the single yarn twist.

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