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IMPACT OF TWIST FACTOR ON THE PHYSICAL AND STRUCTURAL PROPERTIES OF JUTE YARN LINEAR DENSITY

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Abstract

This study investigates the effect of twist factors on the tensile properties of jute yarns with linear densities of 193, 213, and 251 tex. The yarns were twisted to four levels: 1460, 2420, 2820, and 3056 turns per metre x √Tex. Tensile testing was conducted according to ASTM D2256 standards to analyse tenacity, elastic modulus, breaking force, and elongation at break. The results indicate that twist factors significantly influence the tensile properties of the yarns. Notably, yarn SY251T153 exhibited the highest tenacity at 28.4 cN/Tex with an optimal twist factor of 2420, highlighting the critical balance between yarn strength and twist. The findings emphasise the importance of optimising twist factors to enhance yarn performance, providing valuable insights for producing high-quality, durable yarns for natural fibre-reinforced polymer composites in structural applications. Statistical validation through one-way ANOVA confirmed significant differences in yarn tenacity with varying twist factors, with p-values of 0.00197 for SY193, 0.0000137 for SY213, and 0.0000879 for SY251, all below the 0.05 threshold. These results underscore the significant impact of twist factors on yarn strength.

Keywords: Natural composites, Yarn twisting, Jute yarn, Twist factor, Yarn linear density.

Introduction

The use of natural fibre-reinforced polymer composites as a replacement for synthetic composites continues to attract research into many areas of application, including recent research into the use of spun yarn to produce structural composites to replace synthetic composites in some structural areas [1].

Jute fibre, a natural fibre derived from bast plants, is a promising reinforcement in natural fibre polymer composites. Its potential as a viable alternative to synthetic composites in various application sectors is a key focus of current research. In this context, the use of spun yarn to produce structural composites is being explored, with this study contributing valuable insights into the impact of twist factors on yarn strength.

Spun yarn is formed by twisting short fibres together, known as staples, to produce a continuous strand suited for further use. The twist factor in yarn making, denoted as K_T, It is a critical parameter that influences the physical and structural properties of spun yarn, including strength, elasticity, and overall performance [2]. It is calculated by multiplying the twist per meter (TPM) by the linear density of the yarn in Tex units (Equation 1) [3].

$$Twist\ factor(K_T) = Twist\ (TPM) x \sqrt{Tex} \quad (1)$$

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Numerous studies have been carried out on the effect of yarn linear density and twist on yarn's physical and structural properties and how this can affect the mechanical properties of their composites [4-6], but relatively little work has been done on the effect of twist factors on the physical and structural properties of the jute yarn [7]. Other factors that can affect the tensile properties of yarn were also investigated, such as the type of plant fibre, an example of which is the bast plant (jute plant), which provides greater strength and modulus due to the higher cellulose content [8]. However, the fibre properties depend on its chemical composites, extraction methods, growing conditions, and modifications; all these will determine the tensile strength and elongation of the yarn [9]. Reports have shown that longer and finer fibres increase the frictional resistance of fibres to slippage and enhance maximum strength during spinning, making the bast plant fibres more popular for yarn production for structural composites [10]. Tyagi [10] concluded that fibre strength determines the strength of the yarn produced and that only 40-65% of the strength of fibre is transferred to yarn strength.

According to Dlodlo et al. [11] and Jones & Rosenblum [12], yarn strength increases with twists up to the optimum twist level, and beyond this level, yarn strength declines; however, this varies for different yarns.

Textile industries have set standards for twist levels to ensure that necessary yarn strength is produced based on their purpose [13]. However, composite manufacturing currently relies on the optimum twist level; hence, research into the best twist level for yarn linear density to produce natural composites with competitive mechanical properties continues [14].

Various studies have investigated the effect of yarn linear density and twist on natural fibre-reinforced polymer composites and concluded that twisting keeps the yarn integrity and strength; it negatively affects the fibre orientation in the yarn, causing fibre misalignment, which eventually will affect the strength of their composites [15, 5, 6,16, 17]. Therefore, establishing a relationship between the fibre properties and twist factor to produce high-performance jute fibre-reinforced polymer composites becomes crucial. This study prepared three different jute yarn linear densities that are twisted using four different twist factors to investigate the impact of twist factors on their physical and structural properties.

While the majority of previous studies have examined the effects of yarn linear density and twist on yarn properties, this paper uniquely emphasises the twist factor (K_T) and its influence on jute yarn's physical and structural characteristics. The twist factor is crucial as it affects yarn strength, elasticity, and overall performance [18].

Materials Selection

This research used three different jute yarns with linear densities of 193, 213, and 251 tex. These yarns were supplied by Bonanza Jute Composites & Diverse Factory, Ltd. from Bangladesh. The jute yarns had a nominal twist factor of 2420 $turns\ per\ metres\ x\sqrt{Tex}$. To retwist the yarns, additional twist factors of 1460, 2820, and 3056 were used, resulting in a three-by-four factorial design for the research material, as shown in Table 1.

Yarn retwisting

Before retwisting, the linear densities of the yarns were confirmed using the skein, and the twist level before and after was confirmed using the twist metre shown in Fig. 1; the yarn was retwisting in the University of Manchester Textile laboratory using a Calvani yarn twister.

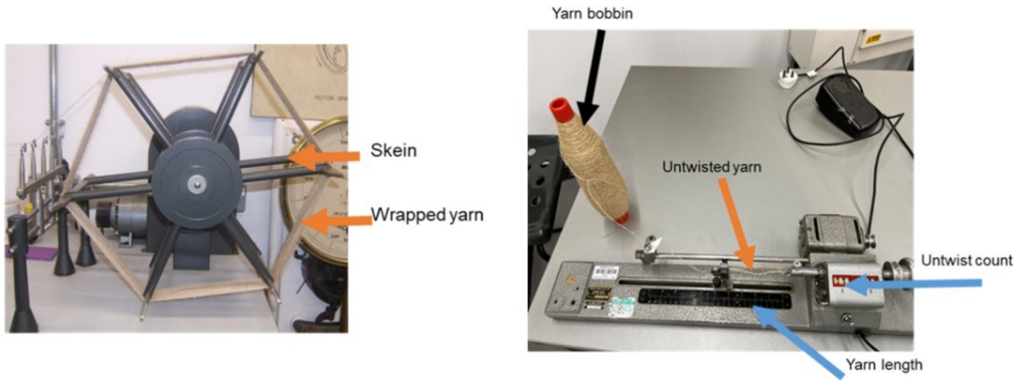

Fig. 1. Skein and twist metre

Table 1. The three-by-four factorial designs of the project yarn bobbins

Jute Yarn Count		Twist factor (√ (tex) x turns per meter),			
		1460	**2420**	**2820**	**3056**
Tex	**Ib/synpdle**	**TPM**	**TPM**	**TPM**	**TPM**
193	5.6	105	174	203	220
213	6.2	100	166	198	200
251	7.3	90	153	177	190

Characterization

Measurement of the jute fibre and yarn physical property

As shown in Figures 2 and 3, the cross-sectional areas of the jute fibre and the newly twisted yarn were measured using a cross-sectioning kit.

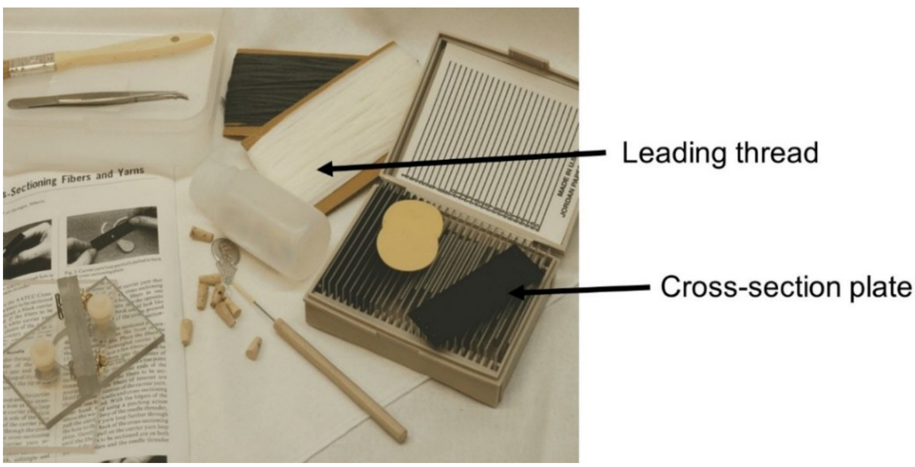

Fig. 2. Fibre and yarn cross-sectioning kit

Fig. 3 shows the procedure and steps for measuring the fibre and yarn cross-sectional areas under a digital microscope (you can read more about this procedure in [19].

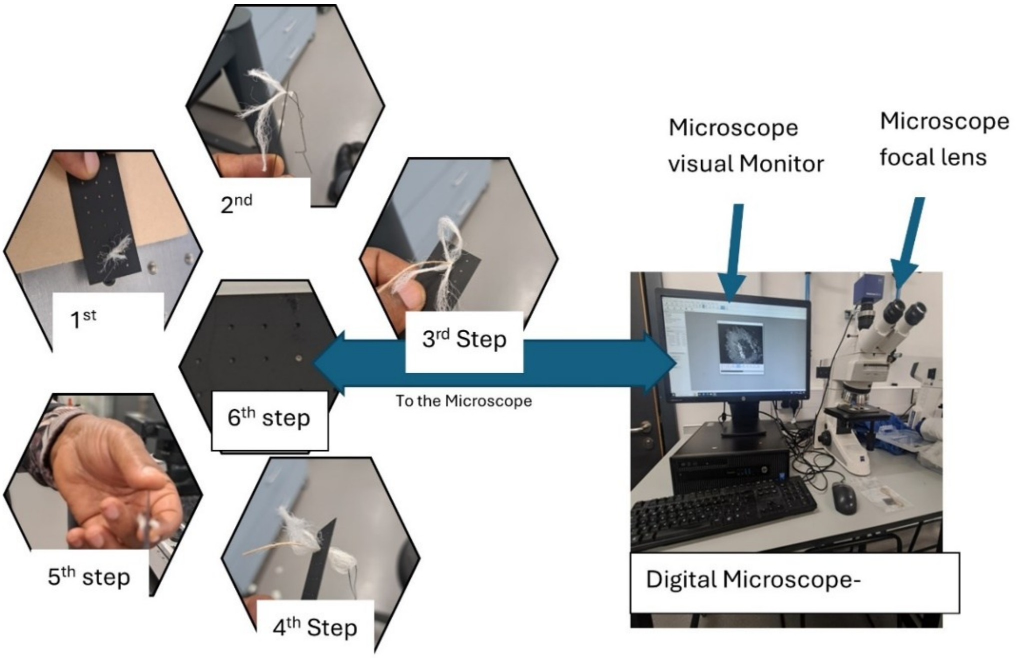

Fig. 3. Complete illustration of how to prepare and measure the cross-sectional areas of the jute fibre and yarn using a digital microscope measuring tools

Fibre preparation for cross-sectional area measurement

Yarn samples were taken from the three jute yarns obtained from Bonanza Jute Composites & Diverse Factory Ltd. in Bangladesh. The fibres were extracted by untwisting the yarns and soaking them in an 80/20 ethanol solution to remove any unwanted attachments. After being stirred, the fibres were poured over a sliding glass and left to air dry for 48 hours. Fig. 4 shows a dried-up image of the fibres.

Fig. 4. Jute fibre extracted from jute yarn

The individual fibres isolated from the cleaned fibre were combined together, passed through the cross-sectional plate, and viewed on a digital microscope. Pictures of the viewed fibre cross-section were taken and processed with image J for easy measurement of twenty (20) randomly chosen cross-sectional areas of the fibres. Fig. 5(a, b) illustrates a cross-sectional plate filled with fibre cross-sections and the picture of the viewed fibre cross-sections of the fibres.

Fig. 5. (a) Cross-sectional plate filled with fibre cross-section, **(b)** Digital image of the fibre cross-sections.

The results of the randomly chosen jute fibre cross-sectional areas (C.S.A) were statistically analysed, and the results obtained are presented in Table 2, which shows the average cross-sectional area of the jute fibre as 419.97µm^2

Table 2. The statistical mean and coefficient of variation of measured jute fibre cross-sectional area

Properties	Mean	Standard Deviation	SE of Mean	Coefficient of Variation
Area(µm^2)	4191.97	1232.76	389.83	0.29

Yarn cross-sectional areas

Ten samples were taken from 250mm of each yarn to determine their cross-sectional areas based on their linear densities and twists. The cross-sectional areas of the yarn from the carrier thread were measured individually using a Microscope measuring tool, as shown in Fig. 6. The results of the ten samples were statistically Analysed using Origin software for each individual yarn, and their statistical means are presented in Table 3.

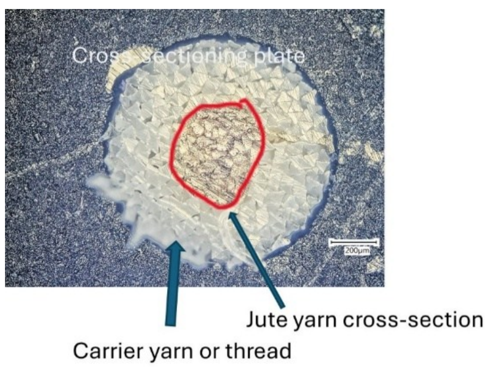

Fig. 6. Typical example of the jute yarn cross section obtained from Digital Microscope against the carrier yarn

Tensile testing of jute fibre and yarns according to their twist factors and linear densities

Examination of the tensile characteristics of jute fibre will help us better understand the strength of the fibres that make up the yarn. Yarn tensile testing is imperative for a comprehensive understanding of how the twist factors affect the tensile properties of twisted yarns according to their linear densities.

Table 3: Statistical results of yarn cross-sectional areas affected by the twist factors.

Yarn Samples	Mean (um^2)	Standard Deviation	SE of mean	Coefficient of Variation
Y193T105	163225.00	51682.83	23113.26	0.32
SY193T174	199703.40	21831.86	9763.50	0.11
SY193T203	187782.60	9899.28	4427.09	0.05
SY193T220	229220.80	52519.47	23487.42	0.23
SY213T100	216058.00	35428.77	15844.23	0.16
SY213T166	242928.20	43864.83	19616.95	0.18
SY213T198	203032.00	18022.62	8059.96	0.09
SY213T200	348049.00	16707.61	7471.87	0.05
SY251T90	252538.20	37671.21	16847.08	0.15
SY251T153	221598.60	35256.59	15767.23	0.16
SY251T177	298718.80	41262.79	18453.28	0.14
SY251T190	234884.00	50935.74	22779.15	0.22

Fibre tensile testing

According to ASTM D3379-75, ten (10) single fibres were separated from the cleaned fibres extracted from the jute yarn. A paper frame with a 20mm opening between its two ends was prepared (Fig. 7a); the fibres were attached to the paper frame using double adhesive tape. The tensile testing was carried out on an Instron tensile testing machine at the University of Manchester. The machine cell was loaded with 10N, and the cross speed was set at 1mm/min (Fig. 7b) [20, 5].

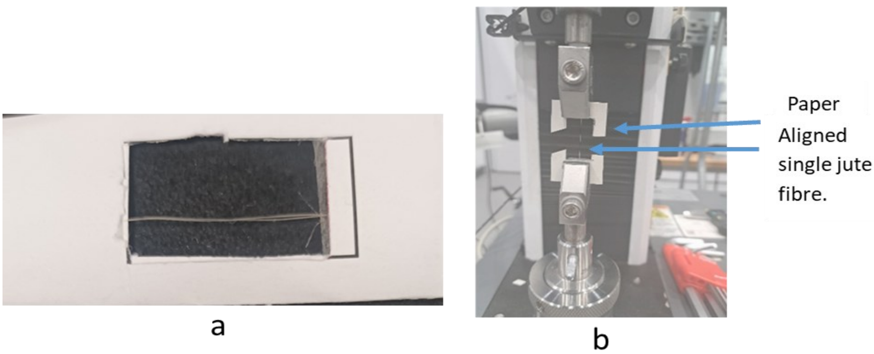

Fig. 7. Instron Universal Tensile Test Machine Setup for Fibre Testing

During the testing, both sides of the paper frame were cut (as shown in Fig. 7b) to release the fibres for tensile testing. The machine has a computer with software that records the tensile activities. Individual fibres were stressed to failure under the load with a constant strain rate of 1mm/min. The fibre individual result was used to create a stress-strain graph in the origin software to determine the fibre's young modulus, tensile strength, and breaking strain. Fig. 8 illustrates the stress-strain.

The statistical mean values of the tested fibres' Young's modulus, tensile strength, and failure strain, as shown in Table 4, agree with the reported literature [20, 21]

Table 4. Statistical tensile properties of jute single fibre

Properties	Tensile strength (MPa)	Elastic Modulus (GPa)	Breaking strain (%)
Mean	332.54	19.85	1.84
Standard deviation	127.65	8.12	0.38
SE mean	40.37	2.57	0.12
CoV	0.38	0.41	0.21

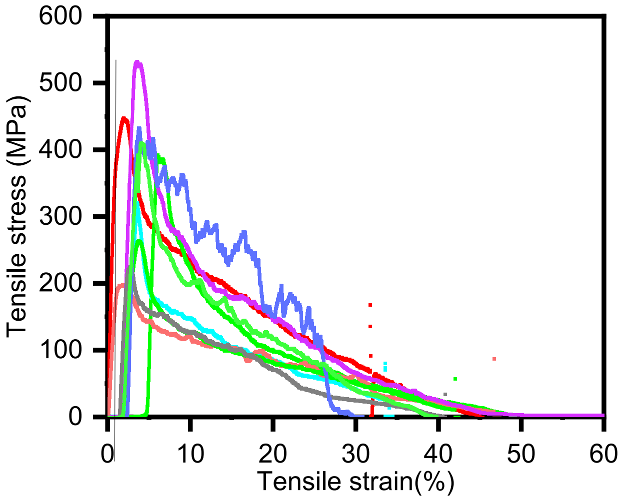

Fig. 8. Stress-strain graph of jute fibre tensile properties

Yarn tensile strength

Five single jute yarn samples were selected, each based on their linear densities and twist factors, to evaluate their tenacity (strength), elastic modulus, breaking force, and elongation at break as affected by the twist factors. The tests were carried out in accordance with ASTM D2256, using a yarn gauge length of 250mm and a machine crosshead speed of 300mm/min. A Universal Testing Machine (UTM) with a 100N load cell was utilised at the University of Manchester workshop. Monkey tape was employed to secure the yarn at both ends, preventing any impact from the vice jaw and isolating the holding points from the yarn's gauge length. The procedure ensures proper alignment of the yarn between the holding jaws for uniform distribution of stress along the yarn gauge length during testing and ensures the accurate measurement of the tensile properties of the yarn. The yarn arrangement in the Universal tensile testing machine is shown in Fig. 9.

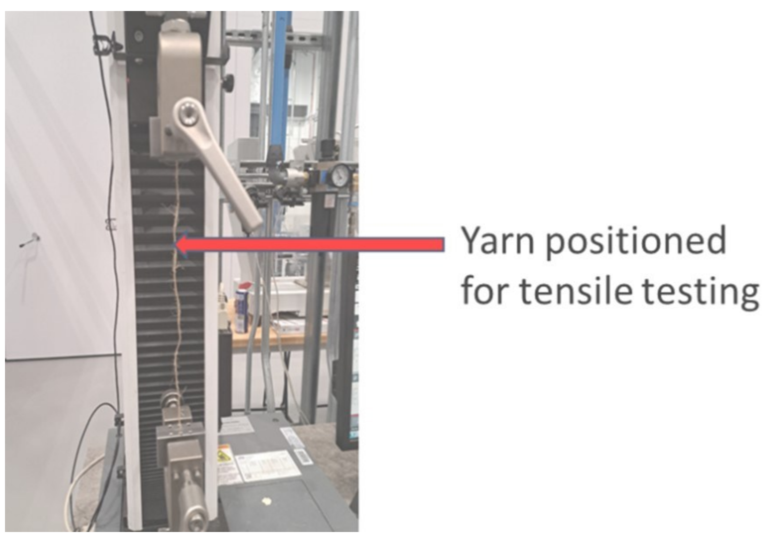

Fig. 9. Yarn tensile testing on an Instron Universal tensile testing machine.

Results

The data obtained from the computer system attached to the machine to record all its activities was used to construct the tenacity-strain graph of the yarn using origin software. All the yarns behaved alike under tension but broke at different points; hence, the statistical means of the samples were calculated, and the report is shown in Table 5. An example of the tenacity-strain graph of the yarn is shown in Fig. 10.

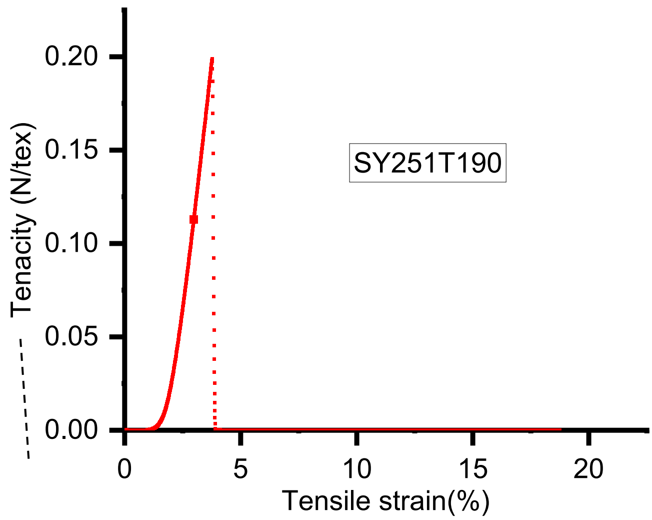

Fig. 10. A typical example of the yarn tenacity-strain graph

The crimp point is not a property of the yarn (Fig. 10). As a result, the graph is only measured after the crimp region has been removed. Fig. 10 depicts a typical example of jute yarn brittleness under tensile force. Table 6 shows the results of the untreated yarn tensile properties based on their linear densities and twists.

Using equation (2), the yarns' modulus of elasticity is derived from the tenacity-strain graph by dividing the graph's maximum tenacity by the breaking strain.

The yarn tensile modulus becomes:

$$(E_y) = {}^{tenacity(\ cN/tex)}\big/_{ensile\ strain(\%)}. \quad (2)$$

The yarn tensile stress:

$$(\sigma_y\,) = {}^{Breaking\ force(N)}\big/_{Cross-section\ of\ the\ yarn(mm^2)} \quad (3)$$

Results and Discussions

Effect of the twist factors on the yarn cross-sectional areas

The study examined the cross-sectional areas of yarns and investigated the impact of different twist factors on these dimensions (Table 5). The twist factors influence the linear density of the yarn (the mass of the yarn per unit length). By introducing twist factors, the yarn density is increased while the cross-sectional area of the yarn is decreased. The reason for this is that twisting causes the compression of the fibres, resulting in a decrease in the space between them. When the yarn can no longer be compressed with more fibre, the linear density of the yarn stays the same. Therefore, additional fibres added for further twisting increase the yarn's cross-sectional area.

Table 5. Statistical tensile properties of untreated jute yarns according to their twist level

Yarn ID	Yarn Tensile Modulus cN/tex	Breaking Force (cN)	Tenacity(cN/Tex)	Elongation (%)
SY193T105	536.76±146.7	2200±837	12.4±4.5	2.27±0.5
SY193T174	813.98±836.6	3000±707	14.6±2.7	1.79±0.2
SY193T203	686.34±148.9	3400±894	17.8±3.5	2.60±0.2
S193T220	818.02±111.1	4400±548	23±3.5	2.80±0.5
SY213T100	341.19±168.6	1800±837	8.0±3.7	2.60±0.7
S213T166	948.15±980.8	4600±894	22±3.7	2.32±0.3
SY213T198	889.23±666.2	4600±894,,	21.4±3.0	2.40±0.3
SY213T200	912.91±114.9	4600±894	21.3±3.3	2.40±0.5
SY251T90	615.57±104.5	3600±894	14.74±3.5	2.40±0.8
SY251T153	984.31±742.1	7200±447	28.4±2.1	2.90±0.1
SY251T177	938.86±139.8	7400±1140	27.8±5.5	2.90±0.33
SY251T190	852.98±929.5	5600±1140	22.6±2.9	2.70±0.9

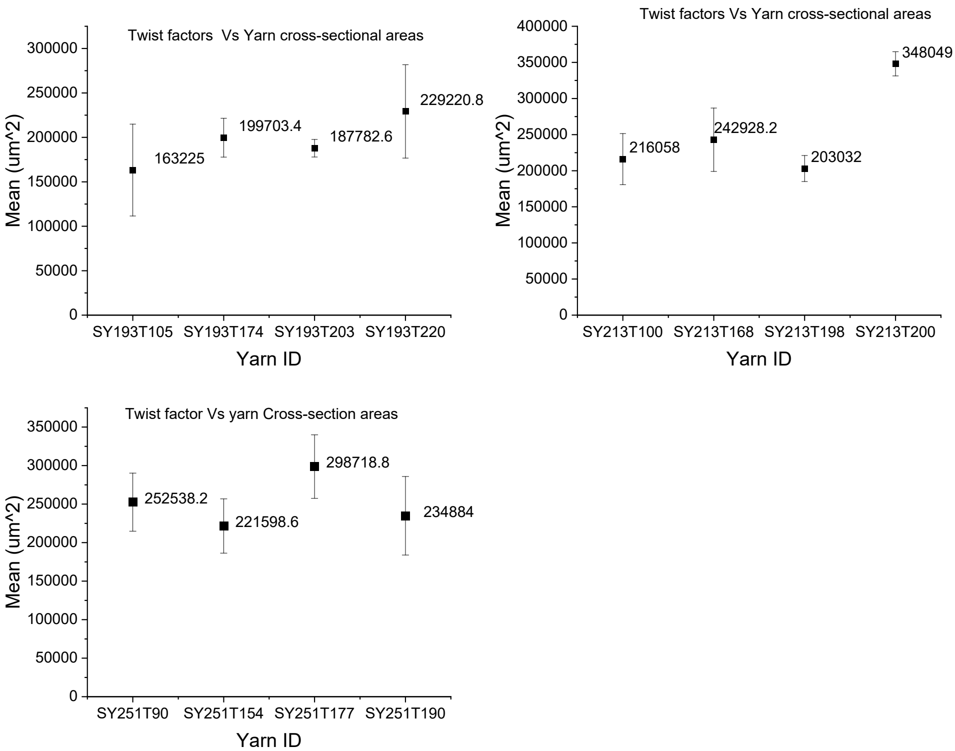

Fig. 10. The graphical impact of the twist factor on the cross-sectional area of yarns according to the linear densities.

Fig. 11 illustrates the changes in the cross-sectional areas of yarn, which are affected by different twist factors for varied yarn linear densities.

The outcomes of this investigation align with the conclusions reported in prior literature.

The study examined how yarns with different linear densities respond to the same twist factor. The results showed that the yarn's linear density significantly affects the twist level when yarns of varying linear densities are twisted with the same twist factor. For example, when yarns of 193Tex, 213Tex, and 251Tex were twisted with a twist factor of 1460 turns per meter × √Tex, the twist level decreased from 105 t.p.m to 100 t.p.m and 90 t.p.m(t.p.m. =turns per metre). The study also revealed that the twist factor has different effects on the cross-sectional area of each yarn based on their linear densities, as illustrated in Fig. 11. These findings align with previous studies by Pan [18], Rask & Madsen [22], Rutkowski [23], and Testex [24].

Statistical analysis of the influence of twist factor on yarn linear densities

The analysis was conducted using a one-way analysis of variance (ANOVA) with Origin software. The findings are summarised in Table 6.

Table 6. ANOVA results of twist factors versus yarn linear density

Source of Variation	DF	Sum of square	Mean square	F Value	Prob>F
SY193tex-Cross-sectional area	3	1.13E+10	3.76E+09	3.238872	0.0962
SY213tex-Cross-sectional area	3	6.5E+10	2.71E +10	3.238872	4.9E-06
SY251-Cross-sectional area	3	1.7E +10	5,67+09	3.238872	0.049219

The ANOVA results show no significant difference in the cross-sectional area of SY193tex. However, there are significant differences in the cross-sectional areas of SY213tex and SY251tex, indicating that the twist factor impacts the yarn differently based on their linear densities.

In conclusion, the ANOVA statistical analysis showed that while the twist factor does not significantly affect SY193tex, it substantially impacts the cross-sectional areas of yarns SY213tex and SY251tex.

Effect of twist factor on the yarn tensile properties according to linear densities

The tensile properties of yarns with different linear densities were tested at four different twist levels. The yarn-breaking force (the force required to break the yarn) increases with an increase in the twist factor, highlighting the significant impact of the twist factor on this property. The yarn's tenacity (strength) also increases with the twist factor up to a certain critical point for each yarn's linear density, further emphasising the influence of the twist factor. Beyond this critical twist factor, the tenacity declines. Each yarn's maximum modulus of elasticity (a measure of stiffness) was realised when there was a balance in the yarn's linear density with the twist factor, underlining the importance of this balance in optimising yarn properties.

Surprisingly, higher twist levels did not cause the yarn to snap under stress, and the elongation at the break did not decrease as expected. This unexpected outcome underscores the significant impact of different twist factors on the elongation at the break of the yarn. The observed increase in yarn resistance to breakage can be attributed to fibre compaction, which reduces the likelihood of fibre slippage or displacement under stress. Furthermore, an increased twist factor enhances the yarn twist level, thereby improving fibre cohesion and leading to better load distribution and resistance to tensile force under stress.

When different yarn linear densities are twisted with the same twist factor, an increase in yarn linear density shows that the twist level is reduced. The combination of the highest linear density and lowest twist level produces the highest breaking force, highest tenacity and elongation at break, showing that the yarns with more linear density require a low twist factor to obtain the optimum property of the yarn for further use. Fibre breakages during the retwisting process can affect yarn tenacity, as seen in SY213T100. Although a low twist level will give high yarn linear densities, however, further increase beyond the yarn optimum twist level will lead to fibre misalignment (obliquity), reducing yarn tenacity, as seen in SY251T190. Fig. 11 graphically illustrates the described effects on yarn tenacity when different linear densities are twisted with the same twist factor.

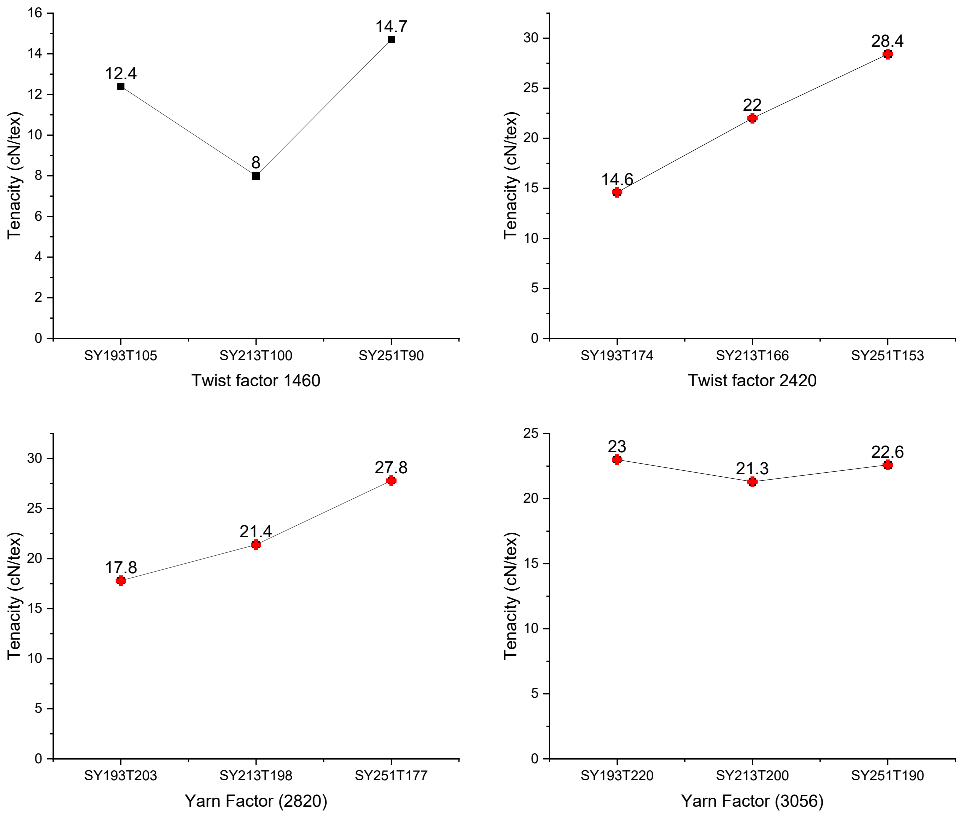

Fig. 11. Yarn tenacity versus twist factor when different yarn linear density is twisted with the same twist factor

Statistical analysis of twist factor on yarn tensile properties according to the linear densities

To confirm the twist factor's influence on yarns' tensile properties according to linear densities and twist level, the results of the tensile testing were statistically analysed using one-way analysis of variance (ANOVA) to analyse yarn tenacity and elongation at break, which is the most important factor for yarn selection, as demonstrated in the ANOVA table below.

Table 7. One-way analysis of variance (ANOVA) of the influence of twist factors on the Tensile properties of yarns according to their linear densities

Source of variation	DF	Sum of Squares	Mean Square	F Value	Prob>F
SY193Tex-Tenacity	3	317.75	105.91667	7.80233	0.00197*
SY213Tex-Tenacity	3	699.3015	233.1005	19.47291	0.0000137*
SY251Tex-Tenacity	3	592.854	197.618	14.25121	0.0000879*
SY193Tex-Breaking stain	3	2.99764	0.99921	11.17563	0.000334*
SY213Tex-Breaking strain	3	0.02388	0.00796	0.10722	0.95465
SY251Tex-Breaking strain	3	0.97242	0.32414	5.44953	0.00894*

*Significantly different

The summary of the various study results of the yarn tensile properties according to linear densities and twists shows that an increase in the yarn twist factor initially increases the yarn strength up to its optimum twist factor. However, further increases in the twist factor cause a decline in the yarn strength. The statistical analysis using ANOVA supported this finding by revealing significant differences in the strength of the analysed samples, with a p-value less than 0.05. This suggests that the twist factor plays a critical role in determining the strength of yarns with varying densities. The high F values and low P values indicate that the twist factor significantly impacts yarn strength. Thus, optimising the twist factors in relation to yarn linear density is crucial to achieving the desired yarn properties.

Conclusion

The study investigated the impact of twist factors on the tensile properties of yarns with varying linear densities. The experimental results demonstrated that increasing the yarn twist factor enhances yarn strength up to an optimum point, beyond which further increases lead to a decline in strength. This finding aligns with the theory of the twist factor's influence on yarn properties.

The statistical analysis, employing a one-way ANOVA, provided robust and unequivocal support for these findings. The ANOVA results revealed compelling evidence of significant differences in yarn strength across different twist factors. For instance, the tenacity of SY193Tex yarns showed a mean square value of 105.91667, an F-value of 7.80233, and a p-value of 0.00197. Similarly, SY213Tex and SY251Tex yarns displayed high F-values of 19.47291 and 14.25121, respectively, with corresponding p-values of 0.0000137 and 0.0000879. These low p-values (less than 0.05) unequivocally confirm the significant impact of twist factors on yarn strength.

Breaking strain analysis further supported these conclusions. SY193Tex yarns had a mean square value of 0.99921, an F-value of 11.17563, and a p-value of 0.000334. For SY251Tex yarns, the mean square value was 0.32414, the F-value was 5.44953, and the p-value was 0.00894, again indicating significant differences due to twist factors.

These findings emphasise the critical role of optimising twist factors to achieve desired yarn properties, particularly for structural applications.

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