Mechanical Properties of Ring-spun Yarn and Its Strength Prediction Model

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Abstract
In this paper, the structural and mechanical properties of ring-spun yarn were studied comprehensively. Relationships between yarn count, yarn twist, and relative yarn structural and mechanical properties were obtained. Through statistical analyses of 200 pure cotton yarn count, twist and strength, with consideration of some influential factors such as being carded or combed, and the application of long-staple cotton, experimental functions of the yarn relative strength with the yarn count and twist were deduced. Considering the above mechanical properties and experimental functions, a pure cotton ring-spun yarn strength prediction model has been established based on continuous mechanics theory. The Equation is easily used with high precision of strength prediction for pure cotton yarn. The relationship between the value predicted and the test value is characterised by high linearity, and the determination ratio of the regression Equation is as high as 0.9623.

Key words: yarn twist, yarn strength, ring-spun yarn, mechanical properties, strength prediction model.

Introduction
Predicting yarn strength with fibre properties and yarn design parameters is very important for reasonable use of fibre raw material, reducing cost and guaranteeing yarn quality. Since the early twentieth century, many researchers have put forward a number of idealist hypotheses on yarn structure and done some research on fibre distribution and tension in yarn using structural and mechanics theory. Subsequently, yarn structural and mechanical properties were analysed using statistics. They have had considerable achievements with respect to the structural and mechanical properties of filament yarn and ring-spun staple fibre yarn [1-4] and have established a number of yarn strength prediction models [5-9]. However, there were some shortcomings as the models were the functions of many unobtainable parameters; hence, prediction precision was limited.

In this paper, the structural and mechanical properties of ring-spun yarn were studied comprehensively, and based on this a single ring-spun yarn strength prediction model was established.

Experiment design and material
Firstly, we made a hypothesis concerning the structure and mechanical properties of single ring-spun yarn according to literature [1, 2]. The relationships between yarn twist and selected yarn structure and mechanical factors, such as the fibre-volume fraction, yarn surface helix angle, the cohesion factor, the slippage ratio, the fibre length efficiency factor and yarn radius were deduced based on the hypothesis.

Secondly, we deduced the experimental correction function of the single ring-spun yarn strength (F) with the yarn count (Nt) and twist (T) using the statistical method. In order to obtain a universally practical function, 200 groups of data for pure cotton single ring-spun yarn (from Changchun Textile Mill and Jiangsu Xingguang Textile Company Limited) with various values of Nt, T and F were collected. The 200 representative yarn samples included all carded and combed yarns generally used and were made of Upland and Sea Island cotton with yarn counts from 5.8 tex to 58.3 tex.

Thirdly, in accordance with continuous mechanics theory, by using the yarn structure and mechanical factors as well as the experimental correction function of the yarn strength with the yarn count and twist, a yarn strength prediction model was established.

Finally, the model was verified using the yarn samples, and a regression function between the yarn strength predicted and tested was obtained. The model achieved high precision for pure cotton ring-spun yarn.

Hypothesis on the structural and mechanical properties of ring-spun yarn
With reference to the analysis of staple fibre yarn by Hearle [1] and Pan [2], the following hypotheses are proposed.

(a) Constitutive fibres have the same properties with a relatively higher elasticity and tension behaviour, in accordance with Hooke’s Law. (b) The yarn cross section is circular and the linear density is uniform along the yarn axle. (c) When a yarn is being extended, the stress distribution along the yarn radial direction is uniform, and there is symmetry along the axle. (d) The trace of fibre in the yarn is a conical helix, and its axle is also that of the yarn. (e) The twist distribution along the yarn radial direction is uniform, and the cohesion is omitted when the twist is zero.

Relationship between twist, yarn structure and mechanical properties
Fibre-volume fraction versus yarn twist
Hearle [10] pointed out that the construction of fibre in yarn is in accordance with the least energy principle so as to keep their equilibrium. The fibre-volume fraction (Vf) is the ratio of fibre volume versus yarn volume, and the Vf value is influenced directly by yarn twist (T). According to data on Vf and the twist relation of Hickie et al [11], Pan [2] obtained the function of Vf and Tt (twist/inch) as Equation 1.

\[
V_f = 0.7 \times (1 - 0.87 \times e^{-0.00495T}) \tag{1}
\]

Converting Tt to T in twist/m, Equation 1 becomes Equation 2.

\[
V_f = 0.7 \times (1 - 0.87 \times e^{-0.00495T}) \tag{2}
\]

Equation 2 is illustrated as Figure 1. When T is low, Vf increases rapidly with...
$T$, and when $T$ reaches a certain value, $V_f$ levels off at its maximum - about 0.7.

**Yarn surface helix angle versus yarn twist**

Studying the relationship between the filament yarn surface helix angle ($q$) and yarn twist $T$, Hearle [10] proposed the following equation:

$$q = \arctg \left[ 0.0001 \times T \times \left( \frac{40 \pi}{\rho_f V_f} \right)^{1/2} \right]$$  \hspace{1cm} (3)

where $T$ is the yarn twist in twist/m, $\rho_f$ - the fibre specific velocity in g/cm$^3$, and $V_f$ is the fibre-volume fraction. Considering the difference between staple fibre yarn and filament fibre yarn, Pan [2] added a correction ratio $a_q$, and when $a_q = 2.5$, Equation 3 becomes as follows:

$$q = \arctg \left[ a_q \times 0.0001 \times T \times \left( \frac{40 \pi}{\rho_f V_f} \right)^{1/2} \right]$$  \hspace{1cm} (4)

Substituting $V_f$ in Equation 4 with equation (2), we obtain the function of $q$ and $T$ as follows:

$$q = \frac{180}{3.14159} \times \arctg \left[ 0.00025 \times T \times \frac{40 \pi}{0.7 \times \rho_f \times \left( t - 0.78 \times e^{-0.001 T} \right)} \right]$$  \hspace{1cm} (5)

When we take $\rho_f$ as 1.53 g/cm$^3$ [16] in Equation 5, we obtain what is illustrated in Figure 2, which shows that $q$ increases nonlinearly with $T$.

**Yarn cohesion factor versus yarn twist**

Fibre in yarn will experience friction and cohesion with surrounding fibres when the yarn is drawn. The cohesion factor $n$ is a non-dimensional factor [2], which reflects the friction and cohesion of a random fibre in yarn. The larger the $T$, the tighter the yarn, and the larger the action of friction and cohesion on the fibre; hence, the bigger the $n$ value is.

According to the graph of $n$ versus $T$ in reference [2], we obtain the inverse exponential curve of $n$ and $T$.

$$n = 0.604 \times e^{-919.4/T}$$  \hspace{1cm} (6)

Taking the influence of fibre length and fineness into consideration, the above equation is corrected with $s$, which is the ratio of fibre length to diameter, which is also a non-dimensional factor; hence Equation 6 becomes Equation 7 as follows:

$$n = 0.0003355 \times s \times e^{-919.4/T}$$  \hspace{1cm} (7)

For Upland cotton, the fibre length is about 25 ~ 33 mm, the diameter - about 17 ~ 20 μm, so, and the ratio of fibre length to diameter is within the range of 1941 ~ 1250. When Sea Island cotton, with its higher length to diameter ratio, is about 25 ~ 33 mm, the diameter - about 17 ~ 20 μm, so, and the ratio of fibre length to diameter is within the range of 1941 ~ 1250.

**Fibre slippage ratio versus yarn twist**

When the yarn is extended to breaking point, a fraction of fibres will break, and the others will slip. The slippage ratio $\lambda$ is the slippage fibre number over the total fibre number at the end of yarn breakage. In accordance with the equation in literature [3] concerning relations between $\lambda$, $n$ and $s$, as Equation 8 reveals, we obtain the power function of $\lambda$, $s$ and $T$, as in Equation 9.

$$\lambda ns \left( 1 - \lambda \right) = t g h \left[ \left( 1 - n \lambda \right) \right]$$  \hspace{1cm} (8)

$$\lambda = 266.8/s \times e^{492.1/T}$$  \hspace{1cm} (9)

When $s = 1700$, Equation 9 is illustrated as in Figure 4, Figure 4 reveals that when $T$ is low, levelling at 0, $\lambda$ increases remarkably, levelling off at 1. The curve means that when $T$ is 0, there is no cohesion among fibres, and when the yarn is drawn to breaking point, all the fibres will slip without breakage.

**Fibre length efficiency factor versus yarn twist**

Considering the results obtained while analysing the force acting on a random fibre in a tensioned state [12], Pan [2, 3] proposed that the length efficiency factor $\eta_l$ of fibres in a yarn is a function of the friction factor ($\mu$) among fibres, the cohesion factor $n$, the fibre length diameter ratio $s$, and the slippage ratio $\lambda$. Moreover, the influence of parameters including $\mu$, $n$, $s$, and $\lambda$ on the yarn mechanical property is entirely revealed by $\eta_{l,c}$, as the following equation shows.

$$\eta_{l,c} = 1 - \lambda + \frac{\tgh \left[ s \mu (1 - \lambda) \right]}{2n s \mu \left( 1 + (1 - \lambda) n s \mu \right)^2}$$  \hspace{1cm} (10)

When $s = 1700$, $\mu = 0.25$ and substituting $n$ and $\lambda$ in Equation 10 with equation (7) and Equation 9, the relationship between $\eta_{l,c}$ and $T$ is plotted as in Figure 5. When $T$ is in a practical range (500 ~ 1200 t/m), $\eta_{l,c}$ increases with that of $T$. This result is just in accordance with
with various values of \( N_t \), and \( F \) from Changchun Textile Mill and Jiangsu Xingguang Textile Company Limited. A conversion was made, with the maximum \( F \) value taken as 1, the other yarn strength values were divided by the maximum \( F \) value and subsequently converted into relative strength values in the range of 0 ~ 1.

Considering the cotton yarn count \( N_t \), carded or combed, and the application of long-staple cotton using statistical analyses, we obtained yarn strength correction functions - **Equation 13** and **Equation 14**. These correction functions possess high precision with a determination ratio of the regression equation as high as 0.9930 and 0.9291, respectively.

**Equation 13**

\[
F_{tx} = 229.28 \times (0.0151 \times N_t + 0.0363) \times N_t^{1.2553}
\]

**Equation 14**

\[
F_t = 2484.703 \times T^{-1.6567}
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**Experimental correction function for yarn strength with the cotton yarn count and twist**

In order to obtain the experimental function of yarn strength \( F \) with the cotton yarn count \( N_t \) and twist \( T \), we collected 200 groups of data of pure cotton yarn and tension test in a yarn \( \phi_y \), and the yarn surface helix angle \( q \) as in **Equation 16**.

\[
\phi_y = \phi / \cos^2 q
\]

According to the continuous medium mechanics theory, the relationship of yarn extension stress \( \sigma_y \), strain \( \epsilon_y \), and modulus \( E_y \) should be as follows.

\[
\sigma_y = \epsilon_y \times E_y
\]

Subsequently, the yarn strength prediction model is established as below.

\[
F = \pi R_y^2 \times \sigma_y
\]

Taking the influence of \( N_t \) on yarn strength into consideration, the \( N_t \) correction function (13) should be multiplied in yarn strength prediction model **Equation 18**.

The above-mentioned relationships between the twist \( T \) and number of structural and mechanical properties, such as \( V_f, q, n, \lambda, \eta_{\phi,\lambda} \), and \( R_y \) are all based on the theory that yarn strength is directly proportional to \( T \). But in reality this is not the case – as shown in **Figure 8**, there is also a diminishing trend of the yarn strength with an increase in yarn twist. Therefore the \( T \) correction function **Equation 14** should be multiplied in the yarn strength prediction model **Equation 18**.

Combining **Equations (12) - (17)** with **(18)**, the final pure cotton ring-spun yarn strength prediction model should be as follows.
F_s = 1345.466 \times V_y \times E_y / \eta_s \times (1 + \cos^2 q) \times (\cos^2 q + \cos^2 q + \cos^2 q) \times (15.1 \times N_y + 63.3) \times N_y^{-1.123}\times 1

Verification of the yarn strength prediction model

In order to verify the prediction precision of the yarn strength prediction model, based on 200 groups of yarn strength data for pure cotton yarn, we took the mean values of the fibre properties as $E_y = 78400000 \text{N/cm}^2$ [16], $\eta_s = 9.5\%$, $s = 1700$, $\mu = 0.25$ and $\rho_y = 1.53 \text{g/cm}^3$ [17], then put all these fibre property values, the cotton yarn count $N_y$ and twist $T$ into the model, and 200 groups of predicted yarn strength values were obtained using calculation software.

Taking the predicted yarn strength ($F_s$) as an independent variable and the test yarn strength ($F_y$) as a dependent variable, we obtained the following linear regression equation.

$$ F_y = 0.9048 F_s + 29.118 $$

$R^2 = 0.9623$ (20)

The regression equation reveals that the prediction precision of the pure cotton ring-spun yarn strength prediction model is very high, with a determination ratio as high as 0.9623.

**Conclusions**

The relationships between the twist $T$ and a number of structural and mechanical properties, such as $V_y$, $q$, $n$, $\lambda$, $\eta_s$, and $R_y$ are in accordance with reality. On the basis of 200 pure cotton experimental data, the $N_y$ and $T$ correction function obtained for yarn relative strength shows high precision. The pure cotton ring-spun yarn strength prediction model deduced shows high precision with a determination ratio of the regression equation as high as 0.9623. As for the application of the model, one simply puts the mean value of cotton properties, such as $E_y$, $\eta_s$, $s$, $\mu$ and $\rho_y$, the yarn count $N_y$ and twist $T$ into calculating software, and a predicted yarn strength value can be obtained. This model may provide some reference for cotton blending and a yarn quality guarantee in a textile mill.

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**References**