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Tensile Properties of Regenerated Bamboo Yarn

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Abstract
The tensile property of regenerated bamboo yarn of 14.58 tex was studied using an HD021N single yarn tensile tester at different tensile speeds (100, 500, 1000, 2000, 3000, 4000, and 5000 mm/min). It was observed that the distribution on diagrams of the breaking strength-frequency and elongation at break frequency of yarn is normal. The breaking strength of the yarn increases when the tensile speed varies from 100 mm/min to 3000 mm/min, then the strength decreases greatly with an increase in tensile speed. The breaking time of the yarn decreases with an increase in tensile speed. A non-linear three-element viscoelastic model was used to simulate the tensile property of the yarn at various tensile rates. The relative error between the theoretical tenacity and actual tenacity is bound to be less than 3%.

Key words: *regenerated bamboo yarn, viscoelasticity, strength, tensile speed, modeling.*

Introduction

Regenerated cellulose fibres, such as cuprammonium rayon, viscose rayon, acetate fibre, polynosic fibre, model fibre, tencel fibre and regenerated bamboo fibre have been used widely [1, 2]. Regenerated bamboo fibre, called ecological fibre [3], has many good properties such as anti-ultraviolet, anti-bacterial and ordo-resistant [4], and is used for functional textile products. Zhang [5] reported that the structure of natural bamboo fibre is similar to that of other vegetable fibres. Wang [6] reported that regenerated bamboo fibre has low strength and high moisture regain compared with natural bamboo fibre. The morphological structure, IR, fibre orientation and breaking strength of bamboo fibre were investigated by Lipp-Symonowicz [7]. Nazan Erdumlu [8] investigated the tensile strength and USTER quality of regenerated bamboo yarn of six different counts. In the last few years on the world market, more and more products from so-called bamboo fibres have appeared. While the characteristics and usage of bamboo bast fibre in various applications have been widely investigated, researches on the tensile properties of regenerated bamboo yarn have so far remained quite limited. The tensile property is one of the most important indices for evaluating the properties of yarn because the yarn supports the tension during knitting or weaving. The low tensile strength of yarn results in low weaving efficiency. The tensile property of textile materials can be described by using viscoelasticity models [9]. Zhang [10] simulated the viscoelastic behaviour of regenerated bamboo fibre and viscose rayon during the tensile process using a linear three-element model.

When a yarn is stretched, both the elastic deformation of the fibres and their rearrangement takes place in the yarn. Depending on the structure of the yarn, deformation may be dominated by a mode or combination of both modes. Compared with other engineering materials such as metals, the deformation of fibres and yarn is highly nonlinear and shows viscoelastic behaviour. The deformation of fibres is also related to the numerous fibre contacts, which is determined by the fibre rearrangement. The deformation of yarn is also highly nonlinear [11 - 13]. Cui [14] reported on the tensile behaviour of soybean protein yarn of different linear density using a non-linear four-element viscoelastic model. The rate of extension has a great influence on the tensile test results of cotton yarn [15]. In this work, a non-linear three-element viscoelasticity model is selected to evaluate the tensile behaviour of bamboo yarn, and the effect of tensile speed on the tensile properties of bamboo yarn is investigated.

Experimental

Pure regenerated bamboo yarn(linear density - 14.58 tex, twist multiplier - 350, and yarn irregularity - 17.3%) was selected to investigate the tensile properties.

The tensile properties of regenerated bamboo yarn were tested on an HD021N single yarn tensile tester (Nantong Hongda Textile Apparatus Co, China). The test conditions were as follows: the test length of yarn was 500 mm; the pretension force - 0.5 cN/tex, and the tensile speed was 100, 500, 1000, 2000, 3000, 4000 and 5000 mm/min.

Results and analysis

Distribution of breaking strength and elongation

The tensile properties of regenerated bamboo yarn at a tensile speed of 500 m/min are shown in ***Table 1***. Each value is the average of 300 yarns.

The distribution diagrams of the breaking elongation-frequency and breaking strength –frequency are normal distribution.

Table 1. *Tensile properties of yarn.*

	Breaking strength, cN	Tenacity, cN/tex	Elongation at break,%	Breaking work, cN·cm	Breaking time, s
Mean	170.04	11.66	11.72	681.12	7.14
Maximum	228.50	15.67	15.34	1058.30	9.25
Minimum	125.00	8.57	6.43	334.20	3.9
Standard deviation	19.60	1.33	1.65	143.62	1.00
Coefficient of variation,%	9.85	11.37	12.27	21.08	14.01

Table 2. *Tensile properties under various tensile speeds.*

Tensile speed, mm/min	Strain rate, %/s	Breaking strength, cN	Tenacity, cN/tex	Elongation at break,%	Breaking	
					work, cN·cm	time, s
100	0.33	158.67	10.89	11.75	626.5	35.41
500	1.67	170.04	11.66	11.72	681.1	7.14
1000	3.33	169.24	11.61	11.74	672.4	3.61
2000	6.67	174.09	11.94	11.06	652.1	1.73
3000	10.00	183.62	12.59	11.56	706.7	1.21
4000	13.33	182.72	12.53	11.25	685.3	0.89
5000	16.67	177.71	12.19	10.62	634.3	0.68

Effect of tensile speed on properties

For different tensile speeds, the tensile strain rate is calculated as follows:

$$K\ (\%/s) = \frac{V}{60L} \times 100$$

where K is the tensile strain rate, V the tensile speed in mm/min, and L the tensile length of the yarn (500 mm).

The effect of the tensile speed on the tensile properties of regenerated bamboo yarn is shown in ***Table 2***. It is observed that the breaking strength increases with an increase in tensile speed. The breaking strength has a maximum value at a tensile speed of 3000 mm/min, then the the breaking strength decreases with increasing tensile speed. However, the elongation undergoes little change at different tensile speeds. The breaking time decreases with an increase in tensile speed. The breaking time decreases greatly when the tensile speed is over 500 mm/min.

The tensile speed influences the breaking time and relaxation deformation time. When the tensile speed increases, the stress relaxation action and elongation decrease, and the strength increases. When the tensile speed lows, the main reason for yarn breaking is fibres slipping. Hence, the breaking strength decreases with increasing tensile speed.

Tensile model of bamboo yarn

The model of non-liner viscoelasticity was selected to investigate the tensile property of regenerated bamboo yarn at different tensile strain rates. ***Figure 1*** shows the model structure. (a) is a non-linear three-element model, and (b) is a non-linear four-element model. In the models, the linear springs (E, E_1, and E_2) represent recoverable fast-elastic deformation under external force action. The Newtonian damper (η) represents irrecoverable plastic deformation under external force action. The non-linear spring

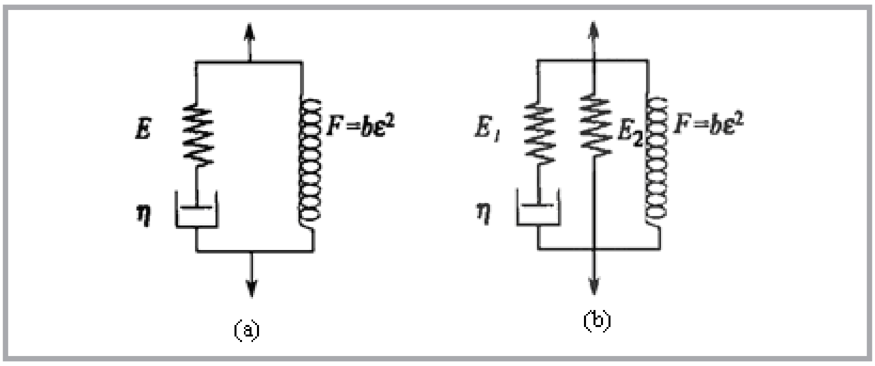

Figure 1. *Model of non-linear viscoelasticity; a) non-linear three-element model, and b) non-linear four-element model, E, E1, and E2 - linear springs, η - Newtonian damper.*

(F) represents the non-linear mechanical property.

For model (a), the deformation of the Maxwell element under external force action is expressed as follows:

$$\frac{d\varepsilon_1}{dt} = \frac{1}{E} \times \frac{d\sigma_1}{dt} + \frac{\sigma_1}{\eta} \qquad (1)$$

The relationship between the deformation and external force for a non-linear spring is as follows:

$$\sigma_2 = b\varepsilon_2^2, \quad \sigma = \sigma_1 + \sigma_2, \quad \varepsilon = \varepsilon_1 = \varepsilon_2$$

Thus the relation between the deformation and external force for model (a) is expressed as follows:

$$\frac{d\sigma}{dt} + \frac{E}{\eta}\sigma = (E + 2b\varepsilon) \times \frac{d\varepsilon}{dt} + \frac{Eb}{\eta}\varepsilon^2 \qquad (2)$$

Because of the equal-speed tension during tensile,

$$\varepsilon = kt$$

Where k is the tensile rate.

Because σ(0) = 0, the relationship between stress and strain for model (a) is expressed as follows:

$$\sigma = k\eta(1 - e^{-\frac{E\varepsilon}{\eta k}}) + b\varepsilon^2 \qquad (3)$$

Set A = kη, B = b, C = E/kη, and consider the pre-tension (σ_0). ***Equation 3*** is corrected as follows:

$$\sigma = \sigma_0 + A(1 - e^{-C\varepsilon}) + B\varepsilon^2 \qquad (4)$$

Model (b) consists of model (a) and a linear spring. Set the stress of the Maxwell element, the stress of the linear spring and the stress of the non-linear spring are σ_1, σ_2 & σ_3, respectively, and the strain is ε_1, ε_2 and ε_3, respectively. The deformation under external force action for model (b) is expressed as follows:

$$\frac{d\varepsilon_1}{dt} = \frac{1}{E_1} \times \frac{d\sigma_1}{dt} + \frac{\sigma_1}{\eta} \qquad (5)$$

$$\sigma_2 = E_2\varepsilon_2,\ \sigma_3 = b\varepsilon_3,\ \sigma = \sigma_1 + \sigma_2 + \sigma_3,$$
$$\varepsilon = \varepsilon_1 = \varepsilon_2 = \varepsilon_3$$

The equation of stress-strain for model (b) is as follows:

$$\sigma = k\eta(1 - e^{-\frac{E_1\varepsilon}{\eta k}}) + E_2\varepsilon + b\varepsilon^2 \qquad (6)$$

Set A = kη, B = b, C = E_1/kη, D = E_2, and consider the pre-tension (σ_0). ***Equation 6*** is corrected as follows:

$$\sigma = \sigma_0 + A(1 - e^{-C\varepsilon}) + D\varepsilon + B\varepsilon^2 \qquad (7)$$

A typical actual tensile curve of regenerated bamboo yarn was studied at different tensile rates and the data of stress and strain in the tensile curve observed. Then the coefficients of ***Equations 4*** and ***7*** were obtained using Matlab software for the optimum least square method. The results are shown in ***Table 3***.

Table 3. *Coefficients of* ***Equations 4 and 7;*** *where A is the tensile rate times the viscosity of the Newtonian damper; C - the linear spring modulus; B - the spring constant of the nonlinear spring; D - the linear spring(E2) modulus; SSE - the residual sum of squares; and R - the correlation coefficient.*

Tensile strain rate, %/s	Equation 4					Equation 7					
	A	C	B	SSE*	R2**	A	C	D	B	SSE*	R2**
0.33	6.344	0.8514	0.03270	0.55323	0.99139	5.008	1.1520	0.3640	0.0111	0.4782	0.9926
1.67	6.962	0.8542	0.03342	0.09973	0.99905	6.557	0.9118	0.1024	0.0275	0.0936	0.9991
3.33	6.24	0.9531	0.03793	0.49186	0.99316	5.645	1.0800	0.1672	0.0279	0.4746	0.9934
6.67	7.385	0.6573	0.03747	0.08469	0.99905	8.608	0.5788	0.2831	0.0534	0.0760	0.9992
10.00	7.531	0.6952	0.03854	0.05557	0.99950	5.857	0.9442	0.4039	0.0155	0.0105	0.9999
13.33	7.694	0.6724	0.03903	0.0326	0.99971	6.380	0.8241	0.3132	0.0211	0.0150	0.9999
16.67	7.217	0.7199	0.04159	0.0244	0.99972	6.086	0.8736	0.2835	0.0248	0.0109	0.9999

Table 3 shows that SSE ≈ 0 and $R^2 \approx 1$, hence models (a) and (b) have high precision when simulating the actual tensile of regenerated bamboo yarn.

Based on the result in *Table 3*, the basic coefficients (E, η, b, and τ) were calculated. The results are shown in *Table 4*.

Theoretically, E, η, b and τ are not related to the tensile rate. However, all coefficients in *Table 5* vary with tensile rate change. The tensile rate has a relatively weak effect on E and b, but a serious effect on η. With an increase in the tensile rate, coefficient b increases, while η and τ decrease greatly.

τ is the relaxation time of the Maxwell unit, which is related to the structure of the fibre and fibre arrangement in the yarn. When the tensile rate increases, the deformation time of the yarn decreases. Hence τ decreases with an increase in the tensile rate.

Put the coefficient in *Table 4* and the actual breaking elongation of the yarn into *Equations 4* and *7*, and the theoretical tenacity of regenerated bamboo yarn at different tensile rates can then be calculated, the results of which are shown in *Table 5*. The relative error is calculated as *Equation 8*.

$$\delta = (V_A - V_T)/V_A \times 100\% \quad (8)$$

where:
δ – relative error in %,
V_A – actual value,
V_T – theoretical value.

The results in *Table 5* show that the relative error for model (a) and model (b) is less than 3%. Hence, both model (a) and model (b) can simulate the tensile property of regenerated bamboo yarn at different tensile rates. A simple non-linear three-element viscoelasticity model can be selected as a tensile model of regenerated bamboo yarn at various tensile rates.

Conclusions

The distributions of the breaking strength and breaking elongation of regenerated bamboo yarn are normal. The breaking strength of bamboo yarn has a high value at a tensile speed of 3000 mm/min. The breaking elongation of bamboo yarn shows little change at a tensile speed from 100 mm/min to 4000 mm/min. A simple non-linear three-element viscoelasticity model can be selected to simulate the tensile model of regenerated bamboo yarn at various tensile rates. The specific tensile strength of bamboo yarn can be obtained according to the model. The relative error between the theoretical tenacity and actual tenacity is less than 3%.

Table 4. *Coefficients for different tensile rates; where η is the viscosity of the Newtonian damper; E - the linear spring (E) modulus in model (a), b - the spring constant of the nonlinear spring, τ - the relaxation time of the Maxwell unit, E1 - the linear spring (E1) modulus, and E2 - the linear spring (E2) modulus.*

Tensile strain rate, %/s	Model (a)				Model (b)				
	η, cN.s/tex	E, cN/tex	b, cN/tex	τ, s	η, cN.s/tex	E_1, cN/tex	E_2, cN/tex	b, cN/tex	τ, s
0.33	1922.424	5.4013	0.0327	355.920	1517.576	5.7692	0.3640	0.0111	263.047
1.67	416.8862	5.9469	0.0334	70.101	392.6347	5.9787	0.1024	0.0275	65.673
3.33	187.3874	5.9473	0.0379	31.508	169.5195	6.0966	0.1672	0.0279	27.806
6.67	110.7196	4.8542	0.0375	22.809	129.0555	4.9823	0.2831	0.0534	25.903
10.00	75.3100	5.2356	0.0385	14.384	58.5700	5.5302	0.4039	0.0155	10.591
13.33	57.7194	5.1734	0.0390	11.157	47.8620	5.2578	0.3132	0.0211	9.103
16.67	43.2933	5.1955	0.0416	8.333	36.5087	5.3167	0.2835	0.0248	6.867

Table 5. *Theoretical specific strength and actual specific strength of yarn.*

Tensile strain rate, %/s	Elongation, %	Actual tenacity, cN/tex	Model (a)		Model (b)	
			Theoretical tenacity, cN/tex	Relative error, %	Theoretical tenacity, cN/tex	Relative error, %
0.33	11.75	10.88	10.86	0.1838	10.82	0.5515
1.67	11.72	11.66	11.86	1.7152	11.82	1.3722
3.33	11.74	11.6	11.47	1.1206	11.45	1.2931
6.67	11.06	11.94	11.96	0.1675	12.00	0.5025
10.00	11.56	12.59	12.68	0.7148	12.60	0.0794
13.33	11.25	12.53	12.63	0.8778	12.57	0.3192
16.67	10.62	12.18	11.90	2.2988	11.90	2.2988

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