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Modelling the Tensile Properties of Modal/Polyurethane Core-spun Stretch Yarn

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Abstract
The tensile properties of polyurethane filaments, Modal yarns and Modal/polyurethane core-spun yarns were tested. The stress-strain relationship of the yarns is analysed using a nonlinear viscoelastic model, and the multinomial relationship between stress and strain is obtained. Curve fitting is also made using the least square method. Theoretical calculations agree with the measured results very well.

Key words: *filament polyurethane, Modal yarn, core spun yarn, tensile properties.*

Introduction

Polyurethane core-spun yarns consist of polyurethane as core fibre, which provides excellent elasticity, and nonelastic fibre as the wrapping cover, which provides certain hand properties, appearance and comfortability. Polyurethane fibre is a manufactured fibre in which the fibre-forming substance is a long–chain synthetic polymer composed of at least 85% of the segmented polyurethane. Polyurethane fibre has excellent elongation and elastic recovery, similar to that of rubber. Its flexibility, abrasion resistance, strength, and resistance to deterioration are better than rubber [1]. Although polyurethane fibre can be made as an uncovered filament, the fibre is always used in conjunction with other fibres, most often in covered or core-spun yarns, where it is covered by other fibres [2 - 4].

Modal is a manufactured fibre of cellulose with a higher breaking strength and wet modulus than that of ordinary viscose rayon, partially overcoming the tendency to wrinkle easily and stretch when wet [1]. It retains the fine characteristics of rayon, such as high absorbency, brighter or dull luster, pleasant hand and feel, good draping qualities, and the ability to be dyed in bright colours.

Core spun yarn is made by the spinning process in which a filament is covered with a sheath of staple fibres [2 - 5]. In core stretch yarn, the core is an elastic filament (usually under tension) and the sheath is composed of staple fibres [2 - 4]. It has all the characteristics of the predominant fibre, together with the added advantage of stretch and recovery, depending on the tension of the elastic core filament. In order to study the tensile properties of core-spun stretch yarns, Modal/polyurethane core-spun yarn and Modal yarns were tested and it was found that the tensile curve of the yarns clearly exhibit a nonlinear characteristic at high strain, especially near the rupture point. Hence a non-linear viscoelastic model has been developed in the paper.

Model for core-spun yarn

The stress-strain curves of polyurethane filament, Modal/polyurethane core-spun yarn and Modal yarn are shown in ***Figures 1 - 3***, respectively. It can be found that there are characteristics of both the polyurethane filament and modal yarn in the stress-strain curve of Modal/polyurethane core-spun yarn. The initial region of a very low slope on the stress-strain curve of Modal/polyurethane core-spun yarn represents the region of stretching of the polyurethane fibre and decrimping of the Modal fibre, for which only very small fibre stresses are developed. The initial low-stress region of the yarn is determined by the polyurethane filament because of its inherently high elasticity, with the length of the region being dependent on the tension imposed on the filament in spinning. Then it is followed by a very rapid increase in stress when the fibre crimp has been fully extended so that further extension of the yarn is possible only by extension of the fibres within the yarn. The region of rapidly increasing stress is, of course, governed by the characteristics and limited by the actual breaking stress of the sheath fibres. It is noteworthy that the characteristic of the polyurethane fibre is evident in the initial region of the curve while that of the Modal fibre is predominant at higher strain.

Although the yield point of the stress-strain curve of polyurethane/Modal core-spun yarn in ***Figure 3*** is not evident, it can yet be described by three regions, called the decrimping, pre-yield, and post-yield regions. The decimping region covers the extension range of between 0 and about 0.7% strain. The pre-yield region extends from about 0.7% to 5% strain, and the post-yield region ranges

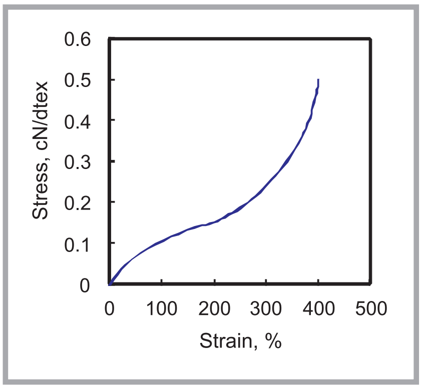

Figure 1. *Tensile curve of polyurethane fibre.*

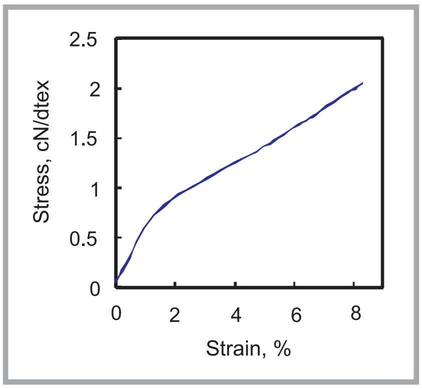

Figure 2. *Tensile curve of 14.8 tex Modal yarn.*

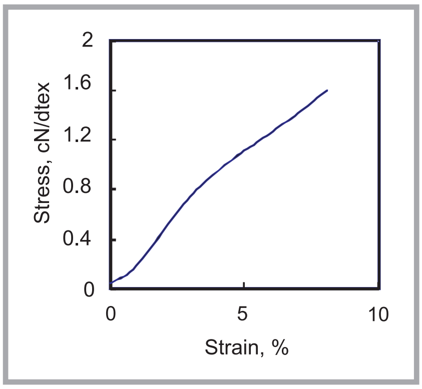

Figure 3. *Stress-strain curve of 14.5 tex Modal/polyurethane yarn.*

from 5% to the breaking point. The precise strain at which the yield point is observed depends on the tension imposed on the filament in spinning and the yield point of the Modal fibre.

In the decrimping region, the stress in the yarn is approximately proportional to the strain. This region, therefore, can be called the ‘Hoboken’ region. In the pre-yield region the stress is proportional to the strain, but they depend on time, hence the fibres are viscoelastic;. thus the yarn is described as linear viscoelastic in the region. If the fibre is stretched into the post-yield region, the slope of the stress-strain curve stiffens abruptly. Once the fibre is stretched into the post-yield region, permanent damage occurs and non-linear deformation appears [6].

Hence, the model should include a linear elastic element that describes the Hookean region in the tensile curve at lower strain, a viscoelastic element which describes the yarn’s viscoelasticity and a non-linear element that describes the yarn’s nonlinear mechanical properties [7 - 11]. For these reasons, we propose a nonlinear model that consists of a linear spring, a Maxwell element which consists of a linear spring and a Newton dashpot in series, and a nonlinear spring in parallel, as depicted in ***Figure 4***.

In the model proposed, a Maxwell element, linear spring and nonlinear spring are placed in parallel. The Maxwell element consists of a linear spring and Newton dashpot in series. The linear springs of modulus E_1 and E_2 are assumed to follow Hook’s law, and the dashpot is assumed to be filled with Newton fluid of viscosity η. For the nonlinear element, the stress is assumed to be proportional to the square of the strain. That is the stress developed in the nonlinear spring is $b\varepsilon^2$, where b is a constant and ε is the strain of the spring. If the yarn is stretched at a constant rate of extension, $\varepsilon = Kt$, where K is a constant, and the initial stress is $\sigma(0) = 0$, then the stress σ of the model [9, 10] is given by

$$\sigma = E_2\varepsilon + b\varepsilon^2 + \eta K(1 - e^{-E_1\varepsilon/\eta K}) \quad (1)$$

Considering the effect of the pre-tension σ_0 (σ_0 = 0.5 cN/tex according to ISO 2062), a correction has to be made since the strain of the yarn is zero at this pre-tension. With this correction, ***Equation 1*** can be revised as

$$\sigma = \sigma_0 + E_2\varepsilon + b\varepsilon^2 + \eta K(1 - e^{-E_1\varepsilon/\eta K}) \quad (2)$$

For practical use, ***Equation 2*** can be written as

$$\sigma = \sigma_0 + A\varepsilon + B\varepsilon^2 + C(1 - e^{-D\varepsilon}) \quad (3)$$

where, $A = E_2$, $B = b$, $C = \eta K$ and $D = E_1/\eta K$.

Because there is an exponential term in ***Equation 3***, it is difficult to calculate the regression equations. To simplify the calculations, we expand the natural exponent as

$$e^{-D\varepsilon} = 1 - \frac{D\varepsilon}{1!} + \frac{D^2\varepsilon^2}{2!} - \frac{D^3\varepsilon^3}{3!} + \frac{D^4\varepsilon^4}{4!} + \cdots \quad (4)$$

Substituting ***Equation 4*** into ***Equation 3***, the following is obtained

$$\sigma = \sigma_0 + (A + DC)\varepsilon + (B - \frac{DC^2}{2})\varepsilon^2 + \frac{DC^3}{6}\varepsilon^3 - \frac{DC^4}{24}\varepsilon^4 + \cdots \quad (5)$$

Equation 5 can be rewritten in a generalised form as

$$\sigma = \sigma_0 + \alpha_1\varepsilon + \alpha_2\varepsilon^2 + \alpha_3\varepsilon^3 + \alpha_4\varepsilon^4 + \cdots \quad (6)$$

where, α_1, α_2, α_3, α_4 and so on are constants.

Experimental

Modal yarns of 9.8 tex (60S) and 14.8 tex (40S) and Modal/polyurethane core-spun yarns of 9.8 tex (60S) and 14.5 tex (40S) were tested using an USTER TENSORPID III at an extension rate of 500 mm/min. The test length was 500 mm, the measuring accuracy - ±0.5 cN, and the pre-tension was 0.5 cN/tex, following ISO 2062. Sixty measurements were made for each yarn in the experiment. The tester gave the breaking strength, breaking elongation, work at rupture, tensile curve and their averages from sixty observations automatically. All the experiments were made at atmospheric conditions of 20 °C and 63% relative humidity .

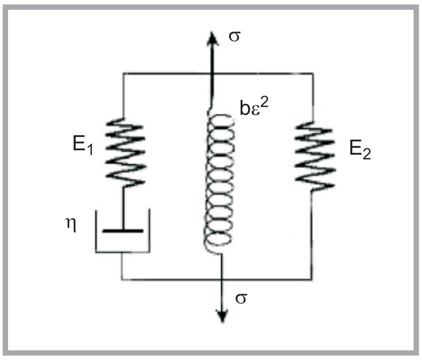

Figure 4. *Nonlinear viscoelasticity model.*

Results and discussion

The tensile properties of Modal yarns and Modal/polyurethane core-spun yarns were measured and the average tensile curves of 60 measurements of each yarn were made, respectively. The average curves were digitised and fitted into ***Equation 6*** using nonlinear regression. Parameters α_1, α_2, α_3 and α_4 were calculated for each yarn, given in ***Table 1***. Theoretical tensile curves were calculated using the parameters in ***Table 1***. A comparison of the measured and fitted average curves for the yarns is illustrated in ***Figure 5 - 8*** (see page 32). The experimental data are depicted as dots and theoretical curves as solid lines. Clearly, very good agreement exists between the fitted and experimental curves.

Comparing the tensile curves of polyurethane filament, Modal yarn and Modal /polyurethane core-spun yarn, it can be found that the tensile curve of Modal/polyurethane core-spun yarn is similar to that of polyurethane filament under low deformation and is similar to that of Modal yarn under high deformation. It is well known that in the core of polyurethane/Modal core-spun yarn is an elastic polyurethane filament, while in its outer sheath there are staple fibres. During the production process of core-spun yarn, the polyurethane filament is stretched about three times. The stress in the filament makes the core-spun yarn retract and the Modal fibres crimp.

Table 1. *Coefficients of the tensile curve of the yarns.*

Parameters	**Fineness**			
	9.8 tex Modal yarn	**14.8 tex Modal yarn**	**9.8 tex Modal/polyurethane core-spun yarn**	**14.5 tex Modal/polyurethane core-spun yarn**
α_1	-0.01883	-0.0117	0.0111	0.0118
α_2	0.3610	0.2454	-0.1874	-0.1911
α_3	-2.2373	-1.7799	9.3442	0.8934
α_4	9.7606	6.9439	0.9535	1.0059
R^2	0.9991	0.9994	0.9988	0.9992

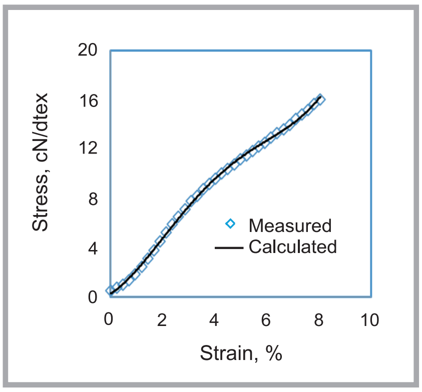

Figure 5. *Tensile curve of 14.5 tex Modal/ polyurethane core-spun yarn.*

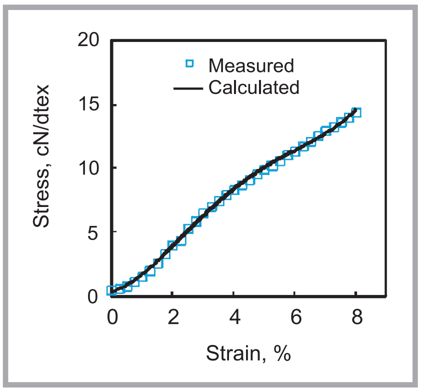

Figure 6. *Tensile curve of 9.8 tex Modal/ polyurethane core-spun yarn.*

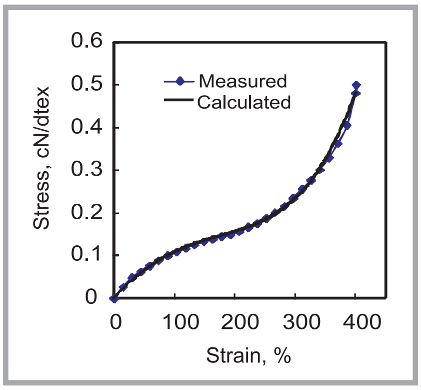

Figure 7. *Tensile curve of a polyurethane filament.*

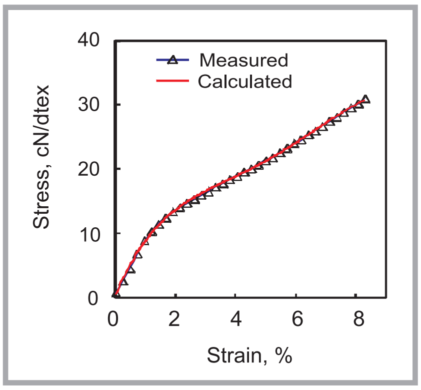

Figure 8. *Tensile curve of 9.8 tex Modal yarn.*

The initial region of the tensile curve of Modal/polyurethane core-spun yarn is similar to that of polyurethane filament, whose elongation is 200% ~ 300%, indicating that the filament determines the shape of the curve at lower strain. As the elongation increases, the Modal fibre that is spun around the filament becomes straight from the curved state and stretches progressively. The stress developed in the fibre increases gradually, and it will dominate the shape of the tensile curve. Therefore, when core-spun yarn is under high strain, its tensile property is governed by the sheath fibres.

In fact, for the stretch-breaking test, yarns may only be taken from a kind of nonlinear viscoelastic material. If other factors that influence the tensile properties are ignored, the relationship between stress and strain is nonlinear, which can be represented by a multinomial function. The more the number of terms or the higher the factorial series, the more accurate the curves are. According to the practical calculations, for most of the yarns, the four factorial series can provide tensile curves with enough accuracy.

Conclusions

In the paper, the tensile properties of polyurethane filament, Modal/polyurethane core-spun yarn and Modal yarn were tested and analysed. A nonlinear model that consists of a Maxwell element, linear spring and nonlinear spring is proposed and used to analyse tensile properties of the yarns discussed. The relationship between the stress and strain of the yarns is simplified as a multinomial function. Fitting is made based on the least square method. Analysing the theoretical calculations and experimental results, the following conclusions can be made:

1. The stress-strain curve of Modal/ polyurethane core-spun yarn is determined by the core and sheath fibres. The shape of the curve is similar to that of polyurethane filament under low strain. As the strain in the yarn increases, the sheath fibres around the core are straightened from the curved state and stretche progressively, where the sheath fibres will dominate the shape of the stress-strain curve of the core-spun yarn under high strain.
2. The nonlinear model presented, consisting of a Maxwell element, linear spring and nonlinear spring, can be used to characterise the tensile behaviour of the yarns.
3. The stress-strain relationship of the model can be represented by a multinomial function. The more the number of terms or the higher the factorial series, the more accurate the curves will be.

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