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RHEOLOGICAL MODELLING OF STRAIN VARIATION OF ELASTIC KNITTED GARMENT

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ABSTRACT

Elastic knitted garment are used in various medical, sport and engineering applications. Knowing the mechanical behavior of such structures is relevant to define its end use. For this reason, four samples are used to study the performance of three rheological models. The result should that Zener model could properly estimate the strain variation of elastic knitted fabric. The model validation was investigated. The results showed that Zener model could be used to predict the strain variation of these structures based on the viscoelastic coefficients of the knitted fabrics.

KEYWORDS

Knitted garment; Viscoelastic; Young modulus; Rheological modeling

1. INTRODUCTION

As an elastic knitted fabric is worn, it is subjected to some forces such as stretching and compression. These forces will influence the mechanical behavior of the garment and in some cases; it may be a source of discomfort. This discomfort is felt when the fabric creates a burden, restrains movement or exerts an overpressure on the body (Li et Dai 2006). In order to overcome this problem, it is relevant to predict the variation of the mechanical performance of elastic knitted fabrics. In this area, several researches were investigated. Choi et al. modeled the mechanical behavior of weft knitted fabrics for outerwear in function of knit structure and stitch density. They concluded that knit structures with combined miss and tuck stitches exhibit properties appropriate for outerwear fabrics for the winter season (Choi et Ashdown 2000). Rheological models are also used to characterize the viscoelastic properties of different materials. Knitted garments present a combination of viscoelastic fluids and elastic solids. Various viscoelastic models have been proposed to simulate the mechanical behavior of several textile materials. Manich et al. employed viscoelastic models to analyze the strain-stress behavior of natural and synthetic yarns (Manich et al., 2000). Halleb et al. developed a rheological model for woven fabrics under strain variation by using technical parameters of fabric structure and yarn (Halleb, Amar, 2008). A new rheological model describing the mechanical behavior of nonwoven fabric is given by Kruncinska et al. (Krucińska et al., 2004). In their study, the nonwoven fabric is considered as an elastic/ viscoplastic material.

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The literature review shows that no studies have been conducted on the rheological behavior of knitted fabrics yet. Such modelling can be useful to knitted elastic garments manufacturers. For this reason, different kinds of weft elastic knitted garment were studied under different stress level in order to modulate their viscoelastic behavior using creep test. Therefore, the aim of this work is to obtain a rheological model describing the strain variation of knitted garment over the time.

2. MATERIALS AND METHODS

2.1. Materials

Simple tensile test were carried out according to the conditions of the standard (ISO 13934-2:2014 (Grab test), 2014) which consist to apply a traction effort at a constant speed 100mm/min to a rectangular fabric sample (50×200mm^2).

The creep tests at different stress levels were also investigated. The different tested samples and their physical parameters are presented in table 1. The parameters taken into account are fiber continent, yarn count, knitted fabric structure, stitch length and areal density. These parameters are considered as the most important ones that influenced more the mechanical behavior of a knitted fabric (Choi, Ashdown, 2000; Asif et al., 2005; Liu et al., 2005; Barhoumi et al., 2018).

Table 1: Physical parameters of tested samples

Sample	Fiber continent	Yarn count (dTex)	Structure	Areal density (g/m^2)	Stitch length (mm)
A	90% PA 6-6 10% Elastane	33 17	Plain	169	2.57
B	90% PA 6-6 10% Elastane	33 17	Pique	188	2.42
C	85% PA 6-6 15% Elastane	77 44	Plain	199	2.77
D	92% PA6-6 8% Elastane	77 44	Pique	232	2.44

As shown in the table above, Plain and Pique knitting structures were used. The presentation of their shapes is given by figure 1 and figure 2.

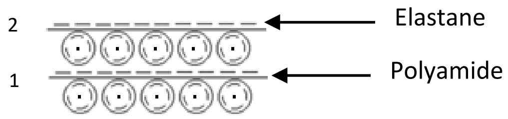


Figure 1. Plain knitting structure

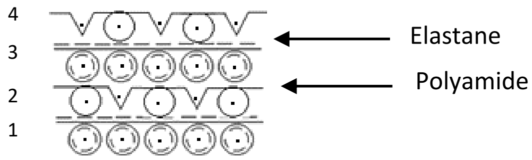


Figure 2. Pique knitting structure

2.2. Rheological modelling

Rheological modeling is used to investigate the viscoelastic characteristics of different materials. In literature, different models are used to simulate the mechanical behavior of yarns, woven and nonwoven fabrics. We can build up a rheological model by combining a linear or a nonlinear elastic spring, a viscous dashpot and plastic skate.

In literature, various model are developed. The most used ones are Maxwell model, Zener model and Kelvin Voight model. Their schematic presentations are shown in figure 3.

In this investigation, creep test has been done to obtain the most suitable rheological model describing the mechanical behavior of knitted structures. The chosen stress values are obtained through the uniaxial tensile test presented in Figure 4. Their values are summarized in the table 2.

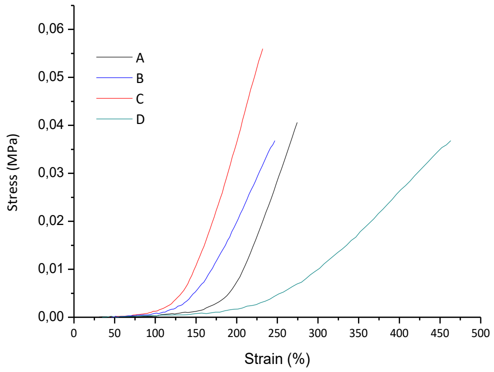


Figure 3. Stress strain curves of the used samples

Table 2: Stress applied for each sample

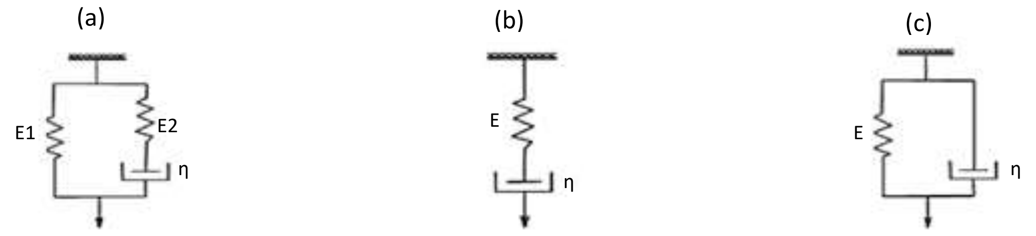
Sample	Stress value (10^{-3} MPa)
A	1.46
B	1.26
C	1.32
D	1.05

In order to investigate the performance of each model, the experimental data was fitted with the derived equations in the figure above. Origin Pro8 software was used and the rheological parameters of each model using the fitting written routine. The rheological coefficient are E and η, they refers the stiffness of the linear spring and the material coefficient of viscosity respectively. τ is the ration of E by η.

3. RESULTS AND DISCUSSIONS

3.1. Fitting performance

The fitting performance of the different models was studied by calculating the root-mean-square error (RMSE) between fitted and experimental data. The RMSE is a frequently used measure of the differences between values predicted by a model or an estimator and the values actually observed (Shcherbakov et al. 2013).



$$\boldsymbol{\varepsilon}(\mathbf{t}) = \frac{\boldsymbol{\sigma}}{\mathbf{E1}}(\mathbf{1} + \frac{\mathbf{E1}}{\mathbf{E2}}(\mathbf{1} - \mathbf{e}^{-\frac{t}{\tau}}))$$

$$\boldsymbol{\varepsilon}(\mathbf{t}) = \frac{\boldsymbol{\sigma}}{\mathbf{E}}(\mathbf{1} + \frac{\mathbf{t}}{\boldsymbol{\tau}})$$

$$\boldsymbol{\varepsilon}(\mathbf{t}) = \frac{\boldsymbol{\sigma}}{\mathbf{E}}(\mathbf{1} - \mathbf{e}^{-\frac{t}{\tau}})$$

Figure 4. Rheological models: (a) Zener model; (b) Maxwell model; (c) kelvin Voight model;

The root-mean-square error is defined as shown in Equation (1):

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{k=1}^{n_d}\left(s_{\mathrm{target}} - s_{\mathrm{fitted}}\right)^2}{n_d}} \qquad (1)$$

Where s_{target} and s_{fitted} are experimental and fitted strain values by the model at the same stress, n_d is the number of the investigated data. In order to make a comparison between the fitting ability of the different applied models, the following criterion was used:

$$\%\mathrm{CV(RMSE)} = \left(\frac{\mathrm{RMSE}}{\bar{s}}\right) \times 100 \qquad (2)$$

The fitting performance of the three rheological models were calculated using Equation (2). Sample A was chosen to assess the most suitable model. The measured values for %CV(RMSE) are presented in Table 3.

Table 3: Performance of different rheological models

	RMSE	%CV(RMSE)
kelvin Voight model	27.48	14.82
Zener model	4.65	2.51
Maxwell model	30.02	16.19

The %CV (RMSE) value of Maxwell model is the higher (16.19%) followed by Kelvin Voight model (14.82%). This result proved that Maxwell and Kelvin Voight models could not fit properly the strain variation. They are composed respectively by a linear and a parallel combination of a linear spring and a Newtonian dashpot. These combinations remains insufficient to describe the strain variation of knitted elastic structures. However, Vangheluwe et al. modeled the viscoelastic behavior of woven fabrics basing on Maxwell model (Vangheluwe et Kiekens, 1997). They found a good accuracy between experimental and rheological model. In addition, Zhong used Kelvin Voight rheological model to study the deformation as a function of time of a braided structure and they proved its precision and validity (Zhong Cai 1995). These results are explained by the specific behavior of knitted garments. They are described by an exceptional extensibility and recovery comparing to other fabric structures. To overcome this discrepancy, Zener model was chosen. It is described for viscoelastic materials having the properties both of elasticity and viscosity (David et al., 2009). Experimentally, Zener model has a reasonable fitting with the lower %CV(RMSE) value (2.51%). This finding proved that this model is highly accurate to model the strain variation of elastic knitted fabric.

3.1. Model validation

In order to prove the accuracy of Zener model, the other samples (B, C and D) are used. Their creep curves are presented in the figures below.

In these figures, theoretical and experimental results are compared. The R^2-values are high and equal to 0.97 for the samples B and D, and 0.98 for C. We can notice that there is a good correlation between the experimental values and the theoretical ones using Zener model. Therefore, this model is qualified as reliable and can be used to predict strain variation of elastic knitted fabrics.

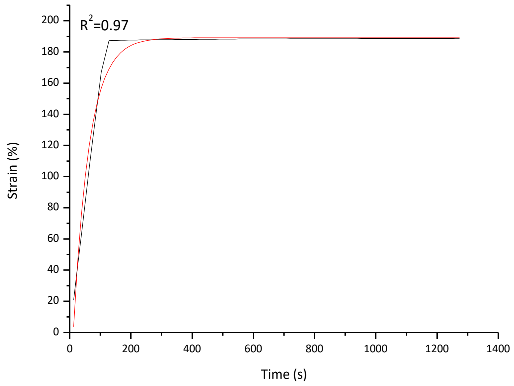


Figure 5. Theoretical and experimental creep curve of sample B

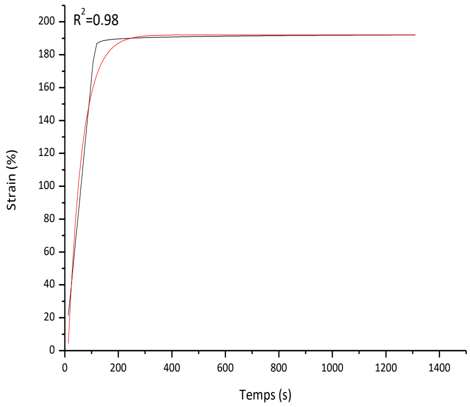


Figure 6. Theoretical and experimental creep curve of sample C

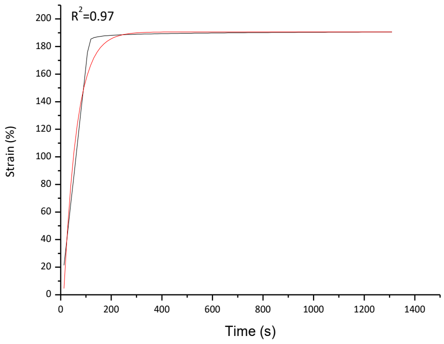


Figure 7. Theoretical and experimental creep curve of sample D

The rheological coefficient for the tested samples are determined and presented in Table 4.

Table 4: The calculated rheological parameters

Sample	E1	E2	η
B	$6.702\ 10^{-3}$	$2.01\ 10^{-3}$	$1.06\ 10^{-3}$
C	$6.92\ 10^{-3}$	$1.41\ 10^{-3}$	$1.09\ 10^{-3}$
D	$5.41\ 10^{-3}$	$0.32\ 10^{-3}$	$0.85\ 10^{-4}$

The table below presents the performance of Zener model to predict the strain variation using the calculated rheological parameters.

Table 5: %CV(RMSE) of the chosen model for the tested samples

Sample	RSME	%CV(RSME)
B	4.76	2.65
C	4.654	2.53
D	4.69	2.57

The obtained values for %CV (RMSE) were in the range of (2.53%, 2.57% and 2.65% for B, C and D respectively) for the fitting performance of Zener model in predicting the strain variation. Therefore, the obtained values for %CV (RMSE) of the developed model were reasonable. Thus, the chosen model is suitable for predicting 0the strain variation of elastic knitted garment.

4. CONCLUSION

Three different rheological models were investigated to find the best configuration to describe the strain variation of an elastic knitted fabric under uniaxial loading. Fitting results showed that Zener model could accurately estimate the creep curves of the elastic knitted structures. The rheological parameters were calculated. These values were used to predict the mechanical performance of other knitted structures using the chosen model. Fitting results of the experimental data with the theoretical equation showed that Zener model was highly accurate in estimating the strain variation and therefore the mechanical trend of such structures.

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