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Analysis of the Creep Properties of Nonwoven Fabric with Mechanical Models

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Abstract
Since nonwoven fabric is widely used in the application of high performance geotextiles, its creep behaviour is essential to be evaluated. In this paper, the creep response of nonwoven fabric was studied by using four mechanical models including the one-term generalised Kelvin model, Burger's model, two-term generalised Kelvin model and Zurek's model. To verify the feasibility of the models, creep experiments for nonwoven fabric were conducted, and the data were fitted by the four models, respectively, to obtain their parameter values using the Marquardt algorithm for nonlinear regression. When comparing the experimental creep curves with those fitted from the mechanical models, it is obvious that the experimental data was best fitted by Burger's model. Also, since the residual sum of squares is far less than that of the GK (n = 1) and GK (n = 2) model and the squares of the correlation coefficient are near to unity, it can be concluded that Burger's model is suitable to describe the creep behaviour of nonwoven fabric. Therefore the viscoelastic model verified can be adopted to predict the creep elongation of nonwoven fabrics.

Key words: *nonwoven fabric, viscoelasticity, creep, mechanical model, nonlinear regression.*

Nomenclature

E_1, E_2	*- stiffness parameters of the viscoelastic model in Pa;*
η_1, η_2	*- viscosity parameter of the viscoelastic model in Pa·s;*
σ	*- stress in fabric in MPa;*
σ_c	*- constant stress in MPa;*
$\dot{\sigma}$	*- stress rate;*
ε	*- strain in fabric in %;*
$\dot{\varepsilon}$	*- strain rate in %;*
T	*- constant resistance of frictional element;*
$K\varepsilon_{2.2}$	*- additional force;*
m	*- weight of piston;*
$\varepsilon_{2.2}$	*- shift of the piston from its initial position.*

Introduction

Nonwoven fabrics are amongst the most widely used in applications ranging from baby diapers to high performance geotextile. At present, nonwoven fabrics account for about 80% of fabric used as geotextile. When constant stress is applied to viscoelastic material, there will be an increasing strain of the material as time goes on. This phenomenon is called creep. Since the ever-growing application of nonwoven and its important creep property in processing and end-use performance of geotextile, it is necessary to characterise the creep behaviours of nonwoven fabrics.

A number of studies [1, 2] have reported the creep behaviors of different types of nonwoven fabrics, but little has been reported about creep simulation with mechanical models. Kim and Pourdeyhimi [3] studied anisotropic mechanical properties and the effects of different processing conditions on mechanical performances. Kim [4, 5] computed the tensile modulus in various directions of the fabric and investigated the relationship between the mechanical anisotropy and geometrical feature of bonded nonwovens. Other researchers [6 - 9] studied the tensile performance of nonwoven fabric with finite element methods by combining the orientation distribution and mechanical properties of fibres. Gautier et al [10] investigated the anisotropic mechanical behaviour of nonwoven geotextiles by using the uniaxial tensile test. The mechanical properties such as the tensile, bending and compression of nonwoven have been studied [11], including the directional dependence of the tensile and bending tests.

Viscoelastic models consisting of springs which obey Hooke's law and viscous dashpots which abide by Newton's law [12, 13] have often been used to characterise the mechanical behaviour of textile materials. For example, the viscoelastic behaviors of fibre, yarn and fabric have been analysed by different mechanical models [14 - 25]. Virginigus et al [26] investigated the creep behaviours of two suit fabrics by applying the generalised Voigt model. The four-element model or Burger's model has been employed to study the creep response of different polymers [27 - 29]. A three-element Zener model was used to characterise the creep behaviour of a thin elastomeric membrane in [30]. Zurek et al. [31] characterise the relaxation of polypropylene monofilament subjected to a tensile load and the compression behaviour of nonwoven fabrics by applying Zurek's rheological model [32]. The results show that there are good agreements between the values of the empirical and theoretical forces as far as relaxation and compression behaviours are concerned. Thus as a kind of polymeric fibre assembly, the creep behaviours of nonwoven fabrics could also be described by mechanical models [13, 16, 21, 22].

In this paper, four viscoelastic models were established to study the creep response of nonwoven fabrics. To verify the feasibility of the models, a number of creep experiments were conducted to obtain data for fitting the theoretical models and achieving their parameter values by applying the Marquardt algorithm. The best model fit was obtained by comparing the experimental creep curves with the fitted ones.

Material

The work in this study is based on thermal bonded nonwovens manufactured by Shenyang high-tech zone Hongxiang Jiaye (China) using polypropylene fibres with a linear density of 1.56 dtex. Carded polypropylene fibres were laid down randomly on a flat surface, and then thermally bonded by hot air (temperature 160 °C, pressure 0.276 MPa), producing nonwoven fabric with 150 g/m^2 area-density. An SEM image of the nonwoven fabric is shown in ***Figure 1***.

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Constitutive modelling

With different combinations of the Kelvin and Maxwell element, we can get a number of viscoelastic mechanical models. It is the purpose of this paper to examine these models and acquire a suitable model for describing the creep behaviour of nonwoven fabric.

In the present study, the creep response of the nonwoven is characterised using four viscoelastic models including the one-term generalized Kelvin ($GK^{n=1}$) model [33, 34], Burger's model [28, 29, 35], two-term generalized Kelvin ($GK^{n=2}$) model and Zurek's model [31, 32]. Schematic diagrams of the models are shown in ***Figure 2***.

1) $GK^{n=1}$ model

The $GK^{n=1}$ model is composed of one Kelvin element and an additional spring in series. In ***Figure 2.a*** the immediate reversible (elastic) deformation is represented by a Hookian spring, the elasticity constant of which is E_2. The delayed, partially reversible (viscoelastic) deformation is represented by the Kelvin model, whose elasticity and viscosity constants are E_1 and η_1, respectively.

The constitutive equation for the $GK^{n=1}$ model is as follows.

$$\sigma + \frac{\eta_1}{E_1+E_2}\dot{\sigma} = \frac{E_1E_2}{E_1+E_2}\varepsilon + \frac{E_2\eta_1}{E_1+E_2}\dot{\varepsilon} \quad (1)$$

As for creep behaviour, assuming constant stress σ_c is applied, creep equations can be expressed from ***Equation 1*** by Laplace's transformation as follows.

$$\varepsilon(t) = \frac{\sigma_c}{E_2} + \frac{\sigma_c}{E_1}(1-e^{-t/\tau_1}) \quad (2)$$

where $\tau_1 = \eta_1/E_1$ is the retardation time.

2) Burger's model

Burger's model has been widely used to analyse the viscoelasticity of materials, with a Maxwell and Kelvin unit connected in series. Differential ***Equation 3*** governs the constitutive relations between the stress σ in MPa and strain ε in %.

$$\sigma + \left(\frac{\eta_1+\eta_2}{E_1} + \frac{\eta_2}{E_2}\right)\dot{\sigma} + \frac{\eta_1\eta_2}{E_1E_2}\ddot{\sigma} = \eta_2\dot{\varepsilon} + \frac{\eta_1\eta_2}{E_1}\ddot{\varepsilon} \quad (3)$$

As for creep behaviour, assuming constant stress σ_c is applied, then $d\sigma/dt$ equals to 0. The creep equation is obtained from ***Equation 3*** by Laplace's transformation as follows.

$$\varepsilon(t) = \frac{\sigma_c}{E_2} + \frac{\sigma_c}{\eta_2}t + \frac{\sigma_c}{E_1}(1-e^{-t/\tau_1}) \quad (4)$$

where $\tau_1 = \eta_1/E_1$ is the retardation time.

The creep behaviour may be interpreted qualitatively by Burger's model as shown in ***Figure 2.b***. The immediate reversible deformation is represented by a Hookean spring and its elasticity constant is E_2. The delayed reversible (viscoelastic) deformation is characterised by the Kelvin model, whose elasticity and viscosity constants are E_2 and η_2, respectively. The instantaneous irreversible deformation is characterised by a Newtonian piston, whose viscosity constant is η_2.

3) $GK^{n=2}$ model

Figure 2.c illustrates the $GK^{n=2}$ model, composed of two Kelvin elements with an additional spring in series. Most textiles do not creep with a single retardation time, as predicted by the Kelvin model. One effective method for characterising the range of retardation times is to construct models consisting of a number of Kelvin elements connected in series, i.e. the generalised Kelvin model.

In the first Kelvin component, the strain is marked as ε_1 and the stress as σ_1, and in the second one as ε_2 and σ_2; the strain and stress of the spring are ε_3 and σ_3, respectively. The total strain is suggested as the sum of the strain of the spring and the first and second Kelvin component, that is, $\varepsilon = \varepsilon_1 + \varepsilon_2 + \varepsilon_3$. While the total stress equals the stress in the first and second Kelvin component and the spring, i.e.: $\sigma = \sigma_1 = \sigma_2 = \sigma_3$.

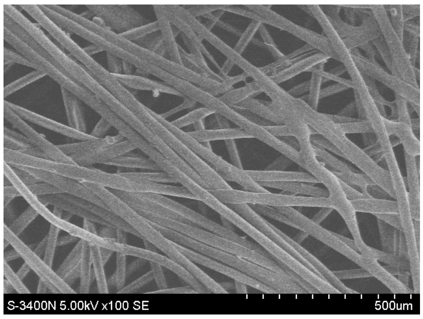

Figure 1. *SEM image of nonwoven fabric.*

The constitutive relation between the stress σ in MPa and strain ε in % is as follows:

$$\sigma + \frac{\eta_1+\eta_2}{E_1+E_2}\dot{\sigma} = \frac{E_1E_2}{E_1+E_2}\varepsilon + \frac{\eta_1E_2+\eta_2E_1}{E_1+E_2}\dot{\varepsilon} + \frac{\eta_1\eta_2}{E_1+E_2}\ddot{\varepsilon} \quad (5)$$

The creep constitutive equation of the models is derived as follows by applying constant stress.

$$\varepsilon(t) = \frac{\sigma_c}{E_3} + \frac{\sigma_c}{E_1}(1-e^{-t/\tau_1}) + \frac{\sigma_c}{E_2}(1-e^{-t/\tau_2}) \quad (6)$$

where $\tau_i = \eta_i/E_i$ ($i = 1, 2$) are the retardation time.

4) Zurek's model

Zurek's model is composed of two parts: 1- a Hooke spring with elasticity constants E_1 and 2 – a Hooke spring with elasticity constants E_2, connected in series with a frictional element of constant

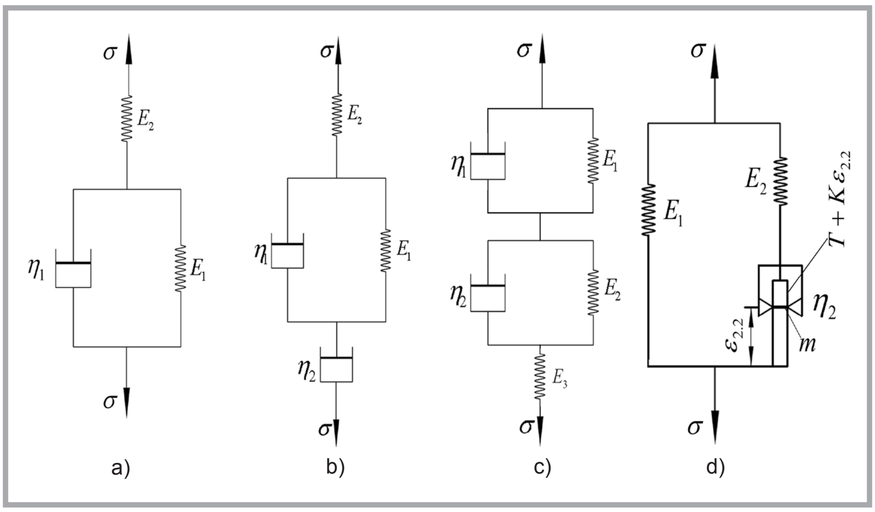

Figure 2. *Viscoelastic models for the strain creep of nonwoven fabrics: a) one-term generalised Kelvin model, b) Burger's model, c) two-term generalised Kelvin model, d) Zurek's model.*

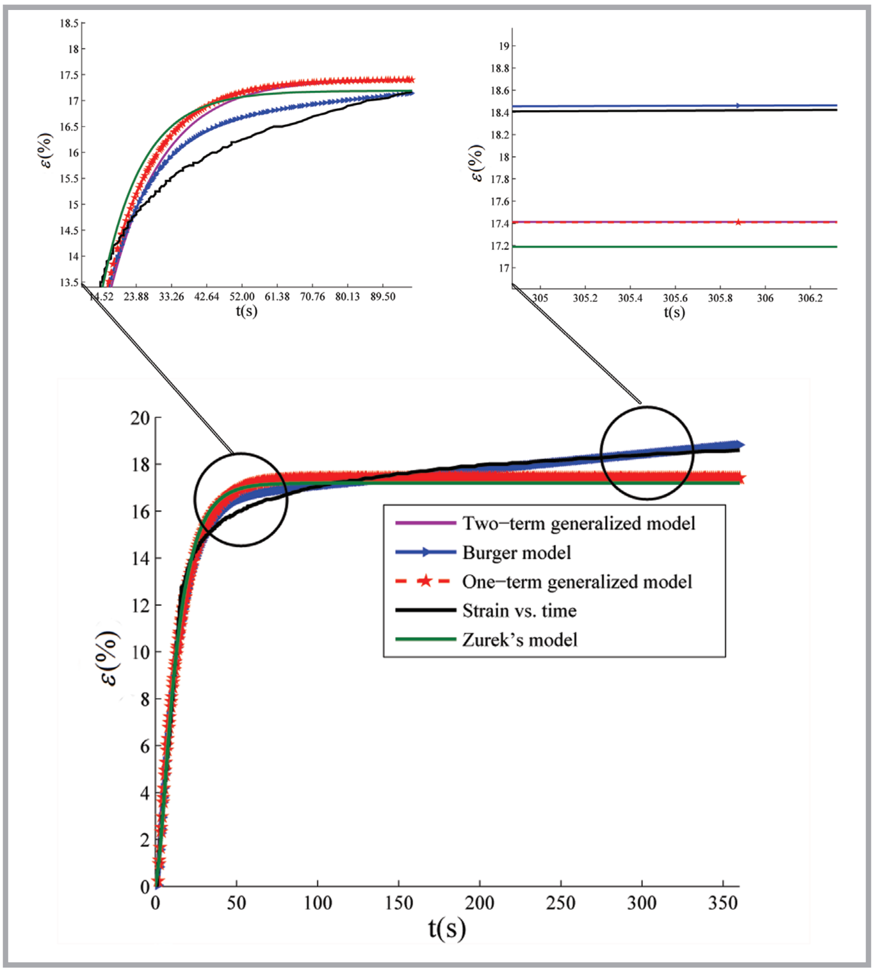

Figure 3. Fitted curves vs. experimental data for nonwoven creep responses.

resistance T and additional force $K\varepsilon_{2.2}$, as shown in ***Figure 2.d***.

Regarding the nonlinear creep behaviour of the nonwoven fabric, we suggest using a frictional element in the rheological model considered. This suggestion is implied from the research work of [31, 32]. The constitutive equation of Zurek's model [31] is as follows.

$$\sigma = \left[(E_1+E_2) - \frac{E_2^2}{m\beta}\right] t\frac{d\varepsilon}{dt} - E_2(At+B)e^{-\frac{\alpha}{2}t} + E_2\left(\frac{\alpha E_2}{m\beta}\frac{d\varepsilon}{dt} + \varphi\right)\frac{1}{\beta} \quad (7)$$

where $\alpha = \frac{\eta_2}{m}$, $\beta = \frac{E_2+K}{m}$, $\varphi = \frac{T}{m}$, A and B are constants.

As for creep behaviour, assuming constant stress σ_c is applied, the Creep equation is obtained from ***Equation 7*** by Laplace's transformation as follows:

$$\varepsilon(t) = \frac{\sigma_c - c}{a}\left(1 - e^{-\frac{a}{b}t}\right) + \left[\frac{E_2 A}{b\left(\frac{a}{b}-\frac{\alpha}{2}\right)^2} - \frac{E_2 B}{b\left(\frac{a}{b}-\frac{\alpha}{2}\right)}\right]\left(e^{-\frac{a}{b}t} - e^{-\frac{\alpha}{2}t}\right) + \frac{E_2 A}{b\left(\frac{a}{b}-\frac{\alpha}{2}\right)} t e^{-\frac{\alpha}{2}t} \quad (8)$$

where $a = \frac{E_2^2}{m\beta} - (E_1+E_2)$, $b = \frac{\alpha E_2^2}{m\beta}$

and $c = \frac{E_2\varphi}{\beta}$.

Table 1. Estimated creep parameters of nonwoven fabric.

Model	E_1, × E+05 Pa	E_2, × E+06 Pa	E_3, × E+06 Pa	η_1, × E+06 Pa·s	η_2, × E+06 Pa·s
GK(n = 1) model	2.43	2.18	-	3.34	-
Burger's model	2.53	2.02	-	3.18	751
GK (n = 2) model	4.90	0.548	4.82	7.39	0.822

Equations 2, ***4***, ***6*** and ***8*** show the theoretical creep behaviour of nonwoven fabric with different models. Creep experimental data will be fitted to the four equations. The constant values of the constitutive equation of any viscoelastic model describing the springs and dashpots of viscoelastic models can be determined semi-empirically by nonlinear regression.

Experimental

The creep properties of nonwoven fabrics were tested in the machine direction using an INSTRON Universal Testing Machine (Instron Co., Ltd., Norwood, MA, USA) under standard laboratory conditions (20 °C, 65% relative humidity). A nonwoven fabric was cut into samples with dimensions of 300 × 50 mm and creep tests were carried out using 10 specimens at a gauge length of 200 mm. The creep tests were conducted at a stress level of 100 N at a strain rate of 0.008 s^{-1}, and then the stress was held constant for 3600 s. The experimentally performed creep curves are shown in ***Figure 3***.

Supposing no changes in the cross-sectional dimensions, the initial strain, ε_0, corresponding to the constant stress applied, σ_0 = 4.76 MPa, is 12.7%. The creep tests revealed that the strain started to grow exponentially from ε_0 to 18.6% in about 360 s and continued to increase approximately linearly with time up to the end of the test duration.

Results and discussion

In this paper, four viscoelastic models were employed to fit the creep behaviour of the nonwoven fabric. Accurate idealisation of the material response involves the selection of an appropriate viscoelastic model, correct modulus and viscosity values of the respective spring and dashpot components.

Predictions of the creep strain at every instant t_i using the creep functions in the models given in ***Figure 2*** were compared with experimental data at that time. In order to get model parameter values, Marquardt algorithm was used to perform the nonlinear regression of ***Equations 2***, ***4***, ***6*** and ***8*** for the creep experimental data curves. The model parameter values were calculated by applying nonlinear regression analysis and are displayed in ***Table 1***. With respect to ***References 31, 32***, Zurek's model is mainly used to describe the relaxation of polypropylene monofilament subjected to a tensile load and the compression behaviour of nonwoven fabrics subjected to compression loads. Since the creep constitutive equation of Zurek's model is very complex, the model parameter values of ***Equation 8*** were not calculated for simplification.

The creep response curves obtained from the three models using the values of corresponding parameters are shown in ***Figure 3***.

The result shows that the total creep strain can be divided into two parts, i.e. instantaneous elastic and viscoelastic deformation. The instantaneous elongation is due to the elastic or plastic deformation of the nonwoven once the external load is applied. This stage is independent of time. In the viscoelastic deformation, the creep rate starts at a relatively high value, but decreases rapidly with time, which may result from the slippage and orientation of polymer chains under persistent stress.

Figure 3 shows the experimental creep results at 100 N and creep curves fitted for nonwoven fabrics with three viscoelastic models. As can be seen from ***Figure 3***, all four models predict a comparable trend of creep strain increasing as an exponential function of time, however, the strain values predicted by the two generalised models and Zurek's model throughout the creep time span are less precise than those by the Burger model, especially in two local magnification areas.

Thus the Burger model can provide a good prediction of creep behaviour for nonwoven fabrics and it has a good consistency with the results [1], which investigated the creep behaviour of nonwovens by modifying the Schapery nonlinear constitutive relation. However, the GK (n = 1) model and Zurek's model cannot fit the experimental data well.

In other words, the accuracy of the models is also evaluated by the residual sum of squares χ_{red}^2 (see ***Equation 9***) and the square of the correlation coefficient R^2 (see ***Equation 10***). The analysis results are shown in ***Table 2***.

Table 2. *Analysis of variance of two models for nonwoven fabric.*

Model	Source	Sum of squares	df	Mean squares	R squares
GK(n = 1) model	Regression	53085.67	3	18061.269	0.79
	Residual	1255.64	418	0.377	
Burger's model	Regression	54215.571	4	12553.893	0.99
	Residual	125.741	417	0.302	
GK (n = 2) model	Regression	53275.58	5	10843.14	0.85
	Residual	1065.73	416	0.302	

$$\chi_{red}^2 = \sum_{i=1}^{n} (y_i - y_i')^2 \qquad (9)$$

where y_1 - experimental values; y_1' - values calculated with the regression analysis; n - number of data points (n = 360).

$$R^2 = 1 - \frac{\sum_{i=1}^{n} (y_i - y_i')^2}{\sum_{i=1}^{n} (y_i - \overline{y})^2} \qquad (10)$$

In simulation, fitting aptness is assessed by comparing the coefficient estimation R^2. The higher the coefficient, the better the model will be fitted to the experimental data. Since the residual sum of squares of the Burger model is far less than that of the GK (n = 1) and GK (n = 2) models and the fact that the square of the correlation coefficient is near to unity, it can be considered that the Burger model is suitable to describe the creep behaviour of nonwoven fabrics. The curves fitted for the creep behavior are represented by the ***Equation 11***:

$$\varepsilon(t) = 2.36 + 0.006t + 18.85(1 - e^{-0.08t}) \qquad (11)$$

With the help of the theoretical model, the creep elongation of nonwoven fabrics after a finite creep time could be predicted.

Conclusions

In practical applications as geotextiles, nonwoven fabrics are subjected to constant tensions resulting in complicated creep behaviours. In this paper, four theoretical models were established to predict the creep behaviour. The creep formulas of the three models were fitted with experimental data to obtain parameter values by applying the Marquardt algorithm.

With respect to the analysis above, we can conclude that the following:

The fitted curve of Burger's model has close agreement with the experimental data. Besides this the residual sum of squares of Burger's model is far less than that of the other models and the square of the correlation coefficient is near to unity. Therefore it can be considered that Burger's model is feasible to describe the creep behaviour of nonwoven fabric and the parameterised Burger model can be used to calculate the creep elongation of nonwoven fabrics in geotextile application.

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