Long-term prediction of creep in textile fibres

Y. C. Bhuvanesh and V. B. Gupta*
Department of Textile Technology, Indian Institute of Technology, New Delhi 110 016, India
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The axial creep of a textile fibre produced from a blend of fibre-grade polypropylene with 5 wt% of commercial atactic polystyrene was measured for 4 h over a range of stresses and temperatures. Using a combined time–temperature–stress superposition principle, a master curve was constructed, taking the reference temperature as room temperature. The master curve was found to cover a period of over 120 years, which is the lifetime of some geotextiles used in reinforcing applications, and could be of interest to designers of such products.

(Keywords: creep; fibre; polypropylene)

Introduction

With the increasing use of textile fibres in geotextiles for reinforcing applications, there is a need to develop appropriate methods for the long-term prediction of fibre creep. Currently available methods for predicting the long-term creep of fibres and polymers include (i) the time–temperature superposition principle[1]; (ii) the empirical equation of Findley and O'Connor[2]; (iii) Sherby–Dorn plots[3]; and (iv) time–stress equivalence[4,5].

In this communication, a simple method based on a combination of methods (i) and (iv) is proposed and applied to an oriented creep-resistant polypropylene fibre. For this fibre, creep data for a period of 4 h over a temperature range of 35–60°C and stresses of 5.3–25.3 MPa were obtained and used to predict creep that is likely to occur over 120 years or more. Theoretical justification for using the proposed approach is also provided.

Theoretical background

The temperature dependence of creep arises from the well-known effect of temperature on relaxation time. If the fibre is assumed to be characterized by single relaxation times, which at temperatures T and T_0 are τ_T and τ_{T_0}, then the temperature dependence of the relaxation time can be characterized by parameter α_T:

$$\tau_T = \alpha_T \tau_{T_0} \qquad (1)$$

In a creep experiment, the strain $\varepsilon^{T_0}(t)$ at time t and temperature T_0 is related to the strain at temperature T by the relation:

$$\varepsilon^{T_0}(t) = \varepsilon^{T}(\alpha_T t) \qquad (2)$$

for all values of t.

Time–temperature equivalence. The equivalence between time and temperature leads to the time–temperature superposition procedures in terms of the shift factor α_T. The temperature dependence of the shift factor may be expressed either in the form of an Arrhenius relation:

$$\ln(\alpha_T) = \frac{E}{R}(1/T - 1/T_0) \qquad (3)$$

where E is the activation energy, R the universal gas constant and T the temperature at which the shift factor is obtained against a reference temperature of T_0, or following the Williams–Landel–Ferry approach:

$$\log(\alpha_T) = \frac{-17.44(T - T_g)}{51.6 + (T - T_g)} \qquad (4)$$

where T_g is the glass transition temperature for the polymer.

The application of the time–temperature superposition principle allows the creep data over a narrow time and temperature range to be reduced to a creep curve for one temperature over a wider time range. Thus the long-range creep behaviour of a product at the temperature of interest can be predicted.

Stress–time equivalence. The application of a stress, like that of temperature, accelerates the relaxation processes, and time–stress equivalence was suggested by O'Shaughnessy[4], Castiff *et al.*[5] and Gruntfest *et al.*[6]. Brody[7] suggested a method for obtaining the shift factor for reducing a creep curve obtained at any stress to a certain reference stress, from the isochronous plots based on the creep curves.

Eyring's model for the flow of polymers. The flow model of Eyring[8,9] provides a basis for analysis of the creep data for fibres. The basic equation of Eyring, equation (5), gives an expression for strain rate based on the reduction in potential energy barrier that has to be overcome for a jump of the molecular kinetic unit to take place:

$$\dot{\varepsilon} = \dot{\varepsilon}_0 \exp(-E/kT) \sinh(\sigma V/kT) \qquad (5)$$

where $\dot{\varepsilon}$ is the strain rate at a temperature T under a stress σ, $\dot{\varepsilon}_0$ is the pre-exponential factor and is a constant, E is the activation energy, V the activation volume and k is Boltzmann's constant.

This formulation can be used to establish the

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* To whom correspondence should be addressed

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equivalence of stress and temperature with time. The apparent viscosity of flow, η, can be obtained from equation (5) by:

$$\eta = \sigma/\dot{\varepsilon} = \frac{\sigma \exp(E/kT)}{\dot{\varepsilon}_0 \sinh(\sigma V/kT)} \tag{6}$$

which at very large stresses simplifies to:

$$\eta = \frac{2\sigma}{\dot{\varepsilon}_0} \exp\left(\frac{E-\sigma V}{kT}\right) \tag{7}$$

Using this equation, the shift factors can be estimated for the two cases considered earlier, assuming that for the range of stresses and temperatures studied, the activation volume is independent of stress and temperature.

(a) Time–temperature equivalence. The time–temperature shift factor, α_T, can be obtained from equation (7) by assuming the viscosity of the polymer to be η_{T_0} at a reference temperature T_0 and η_T at any temperature T under a constant stress σ:

$$\ln(\alpha_T) = \ln(\eta_T/\eta_{T_0}) = \frac{(E-\sigma V)}{k}\left(\frac{1}{T} - \frac{1}{T_0}\right) \tag{8}$$

(b) Stress–time equivalence. If η_1 and η_2 are taken to be the viscosities at any two stresses, σ_1 and σ_2, with the temperature remaining constant at T, the stress–time shift factor, α_σ, can be obtained from equation (7):

$$\ln(\alpha_\sigma) = \ln(\eta_2/\eta_1) = \ln(\sigma_2/\sigma_1) + \frac{(\sigma_1 - \sigma_2)V}{kT} \tag{9}$$

Finally, a combination of stress–time and time–temperature superposition may also be considered, following the above analysis. For the general case of superposition for a polymer exhibiting a viscosity η'' at temperature T'' and stress σ'' to be reduced to conditions T' and σ', at which the polymer viscosity is η', the shift factor $\alpha_{T,\sigma}$ may be obtained as follows:

$$\begin{aligned}\ln(\alpha_{T,\sigma}) = \ln(\eta''/\eta') &= \ln\left(\frac{\sigma''}{\sigma'}\,\frac{\exp\left(\frac{E-\sigma''V}{kT''}\right)}{\exp\left(\frac{E-\sigma'V}{kT'}\right)}\right)\\ &= \frac{E}{k}\left(\frac{1}{T''} - \frac{1}{T'}\right) + \ln(\sigma''/\sigma')\\ &\quad + \frac{V}{k}\left(\frac{\sigma'}{T'} - \frac{\sigma''}{T''}\right)\end{aligned} \tag{10}$$

which is equivalent to the shift arising from time–temperature superposition plus the shift arising from stress–time superposition.

Proposed approach for long-term prediction. The approach proposed in this communication follows from equation (10) and may be illustrated with the help of *Figure 1*, where the creep curves A, B and C have been obtained at (stress, temperature) combinations of (σ_1, T_1), (σ_2, T_1) and (σ_2, T_2), respectively. Curve C, obtained at temperature T_2, can be reduced to a temperature T_1 and superposed on curve B using the time–temperature superposition principle, with a shift factor $\log(\alpha_T)$. The creep curve B and the shifted creep curve C are further reduced to a stress σ_1 to obtain an extended creep curve. The total shift of curve C to curve A is given by:

$$\log(\alpha_{T,\sigma}) = \log(\alpha_T) + \log(\alpha_\sigma) \tag{11}$$

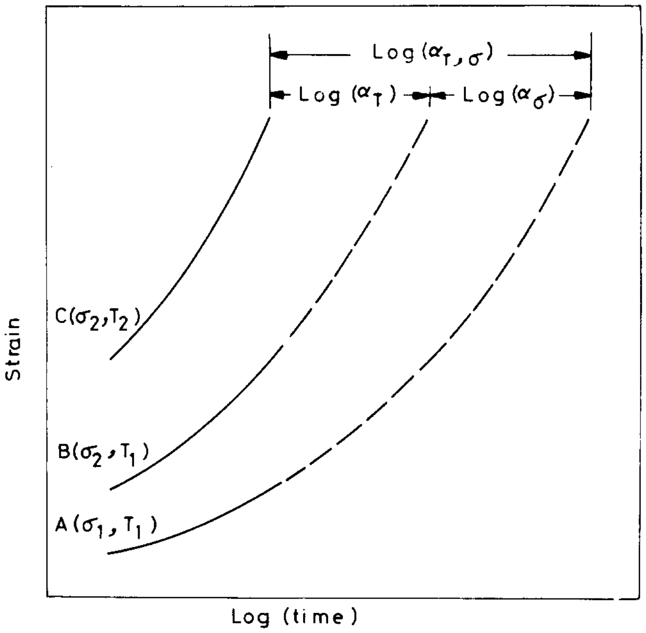

Figure 1 Schematic illustration of the combined time–temperature–stress superposition principle

This approach has been used on a multifilament yarn (described below) using the creep data at four temperatures (35, 45, 55 and 60°C) and four stresses (5.3, 10.5, 15.7 and 20.9 MPa) to predict creep at 35°C for over 125 years.

Experimental

Multifilament yarn was melt-spun on a Fourne Melt Spin Tester (SST 1207) using polypropylene with melt flow index (MFI) of 23, in which 5 wt% of commercial atactic polystyrene had been dry mixed. It was wound at a speed of $750\,\mathrm{m\,min^{-1}}$ and subsequently drawn on a two-zone drawing machine at a take-up speed of $110\,\mathrm{m\,min^{-1}}$ to a total draw ratio of 4.33. The drawn fibre showed a density of $0.902\,\mathrm{g\,cm^{-3}}$ and a birefringence of 0.036. The crystallinity, estimated from density using crystalline density $= 0.946\,\mathrm{g\,cm^{-3}}$ and amorphous density $= 0.854\,\mathrm{g\,cm^{-3}}$, was 53.8%. The load–elongation tests were carried out at an extension rate of $100\%\,\mathrm{min^{-1}}$ on an Instron 4101. The initial modulus of the yarn was found to be $40.6\,\mathrm{g\,den^{-1}}$ while its tenacity was $5.2\,\mathrm{g\,den^{-1}}$. The average extension at break was found to be 23.5%.

A Stanton Redcroft Thermo-Mechanical Analyser was suitably modified to carry out isothermal creep experiments. It allowed temperature control up to an accuracy of ±0.1°C and had a very rapid but gentle loading procedure and an accurate device for measuring increase in length.

The samples were first conditioned by subjecting them to repeated cycles of loading and unloading[10] until they gave reproducible results.

Results and discussion

Using a combination of stress–time and time–temperature superposition, as described earlier, the creep data obtained at different stresses and temperatures were reduced to a temperature of 35°C and stress of 5.3 MPa. It was possible to achieve this by a simple horizontal shift of the data on the logarithmic time axis, and the master creep curve so obtained is shown in *Figure 2*. The

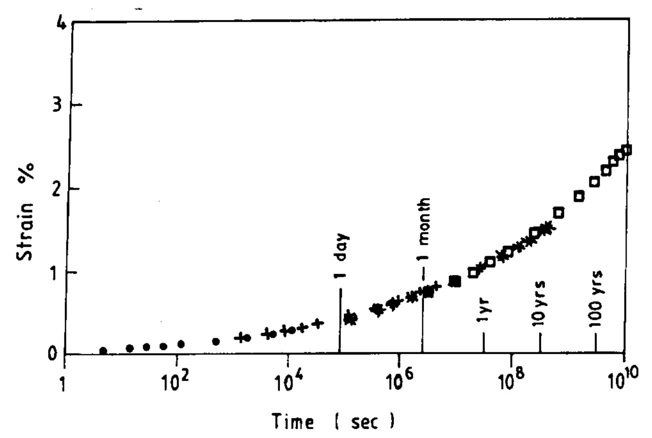

Figure 2 The master creep curve for fibre produced from a blend of polypropylene with 5 wt% of atactic polystyrene at a temperature of 35°C and stress of 5.3 MPa. ●, 5.3 MPa, 35°C; +, 10.5 MPa, 45°C; *, 15.7 MPa, 55°C; □, 20.9 MPa, 60°C

Table 1 Shift factors used for obtaining the master creep curve

Stress (MPa)	Temperature (°C)	Log(α_T)	Log(α_σ)	Log($\alpha_{T,\sigma}$)
5.3	35	0.0	0.0	0.0
10.5	45	0.80	1.65	2.45
15.7	55	1.41	3.00	4.41
20.9	60	1.78	4.03	5.81

corresponding shift factors, including the individual contributions arising from the stress–time and time–temperature shift factors and the total shift factors, are shown in *Table 1*. It is noteworthy that the predicted creep curve covers a period of over 120 years, which is the expected lifetime of some geotextiles used in reinforcement applications and could thus be of interest to designers of such products.

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