Theoretical model for predicting creep behaviour of nonwoven fabrics

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A model has been developed to predict the creep behaviour of nonwoven fabrics using the fibre creep data and the structural parameters of the fabric. A network structure of the constituent fibres of nonwoven fabric is considered and creep strain has been estimated for constant stress creep condition. The changes in the structural parameters due to creep strain have been incorporated in the model. The model has been used to obtain theoretical creep curves for different nonwoven fabrics and these curves have been compared with experimental creep curves.

Keywords: Creep behaviour, Nonwoven fabric, Theoretical creep curves

1 Introduction

Nonwoven fabrics are increasingly used in various applications due to their excellent tensile and hydraulic properties and have shown tremendous growth in the last 25 years. In geotechnical engineering alone, more than 100 specific application areas of these fabrics have been developed where the fabric at least performs one of the four functions, viz. separation, reinforcement, filtration and drainage. However, in most of the cases, nonwoven fabrics perform more than one function at a time. The satisfactory field performance of nonwoven fabrics in any application in general and reinforcement in particular depends largely on the tensile stress-strain characteristics of these fabrics. Properties of nonwoven fabric depend on fibre properties, fibre arrangement in the web and bonding method used in the production of the fabric. A number of properties of nonwoven fabrics depend on the tensile properties of the constituent fibres and the structure of the fabrics.

The tensile modulus, tensile strength and time dependent deformation (creep) of nonwoven fabrics are the most important properties for the performance of these fabrics in the civil engineering structures. Under sustained load, the strain in the fabric increases with time and fabrics can be ruptured on sustained loading over the period of time at loads much lower than their short-term failure loads. Creep behaviour of nonwoven fabrics determines the long-term performance of these fabrics in many civil engineering structures.

If the creep characteristics of the constituent fibres and the details of the fabric structure are known, it should be possible to relate them theoretically to the creep behaviour of nonwoven fabrics. In case of nonwoven fabrics, the structure of web is determined by the orientation of fibres and the bonding method used to bind the web to form the fabric.

A number of studies [1-13] have been reported on theoretical understanding of relationship between structure and tensile behaviour of different types of nonwoven fabrics. However, these studies are mostly related to the short-term mechanical behaviour of these fabrics. In this paper, a theoretical model has been proposed for predicting the creep behaviour of nonwoven fabrics using the experimental fibre creep data and the structural parameters of nonwoven fabrics.

2 Creep Behaviour of a Fibre Network

The fabric creep depends on the creep characteristics of the individual fibre in a network of fibres in a nonwoven fabric, structure of the fabric and the stress developed in different fibres of the network. Load on the individual fibres depends on the inclination of fibres to the direction of applied load and their number in the network as the total load applied on the fabric has to be shared by the fibres in the network. The creep of the network can be estimated by using the fibre creep behaviour and the structural parameters of the network.

The fibre arrangement in the network structure is quite complex in case of nonwoven fabrics (Fig. 1). Actual nonwoven network comprises many fibres at different inclinations in the web which is bonded to form nonwoven fabric. When a nonwoven fabric is...
subjected to a constant load, the deformation of the fabric consists of an immediate extension occurring mainly due to the structural elongation and instantaneous extension of fibres followed by a delayed extension, or creep, which continues with time. The structural rearrangement involves the removal of fibre crimp and reorientation of fibre segments. Both the constructional aspects and polymer properties play important part in the instantaneous elongation and creep resistance of a fabric. Whatever be the bonding method used for making of nonwoven, after the initial deformation, further deformation in the fabric occurs mainly due to the extension of the fibres and the changes in fibre orientation. In theoretical model being proposed to predict the creep behaviour of nonwoven fabrics, the following assumptions are made:

- Nonwoven fabric can be regarded as network of fibres arranged in a number of thin layers one above another.
- The fabric is built up from a number of ‘unit cells’ and each cell deforms uniformly under uniaxial stress.
- Each unit cell is considered to be of sufficient size to obviate any local variations in bonding and fibre properties.
- The size of the fibre segment is sufficient enough to estimate the average curl of the fibre in the network and the mean bond-to-bond distance is the same in the fabrics.
- On application of load, structural deformation as well as slippage, if any, occurs initially but thereafter no slippage occurs.

2.1 Equilibrium of Forces in Fibre Network

Let us assume that the fibre network has \( N_F \) fibres each of linear density \( T \) tex, the initial length of the network is \( L_0 \) and the width is \( W \) (Fig. 1). Once the load \( Q \) is applied on the network, there will be instantaneous deformation of this network followed by the time dependent deformation. Let us assume that during the instantaneous deformation, all curl and crimp has been removed and the network consists of straight fibres and length of the network has become \( L \).

Consider a square ABCD of unit area from the network as shown in Fig. 2(a). Creep load on this unit will be \( Q/W \). Let us assume that there are \( n \) layers, each one containing \( n_j \) fibres at an angle \( \theta_j \), as shown.

![Fig. 1](network.png)

Fig. 1 — Network of fibres in a nonwoven fabric stressed with tensile load [\( L_0 \)- Initial length of network, \( W \)- Initial width of network, and \( Q \)-Load]

![Fig. 2(a)](orientation.png)

Fig. 2 (a) — Different orientation of fibres in the area ABCD, (b) Fibres of a particular orientation \( \theta \), in the area ABCD, and (c) Strain in a fibre at an angle \( \theta \), to the test direction.
in Fig. 2(b). Let this unit area comprise a number of unit cells, each one made of a fibre making an angle \( \theta_i \) to the test direction as shown in Fig. 2(c). Alternately, in this unit area (ABCD), if \( n_1 \) fibres are at an angle \( \theta_1 \) to the test direction, \( n_2 \) fibres are at an angle \( \theta_2 \) to the test direction and so on, with \( n_n \) fibres at an angle \( \theta_n \) to the test direction, then the total number of fibres \( (N) \) in the unit area of fibre network will be given by

\[
n_1 + n_2 + \ldots + n_n = N
\]

or

\[
\frac{n_1}{N} + \frac{n_2}{N} + \ldots + \frac{n_n}{N} = 1
\]

or

\[
\sum_{i=1}^{n} \phi(\theta_i) = 1
\]

where \( \phi(\theta_i) \) represents the proportion of the fibres at an angle \( \theta_i \) to the test direction. The \( \phi(\theta_i) \) is called the orientation factor and is given by

\[
\phi(\theta_i) = \frac{n_i}{N}.
\]

Consider \( n_i \) fibres at an angle \( \theta_i \) in the unit area. Out of these \( n_i \) fibres, only \( n_i \cos \theta_i \) fibres will be extending to the both ends (AB and CD) of the unit and thus contribute to the balancing of the creep load. If \( \sigma(t) \) is the stress level in these fibres in N/tex at time \( t \), the contribution of each of the effectively contributing fibre in balancing the creep load will be \( T \sigma(t) \cos \theta_i \). The total contribution of the fibres at angle \( \theta_i \) in balancing the creep load is given by

\[
(n_i \cos \theta_i) [T \sigma(t) \cos \theta_i].
\]

Force equilibrium requires that the contribution of all the fibres at various angles is equated to the creep load, thus

\[
\sum_{i=1}^{n} (n_i \cos \theta_i) [T \sigma(t) \cos \theta_i] = \frac{Q}{W}
\]

or

\[
\sum_{i=1}^{n} \phi(\theta_i) \sigma(t) \cos \theta_i = \frac{Q}{W}
\]

where \( Q/W \) represents the stress level in fabric (force per tex) and can be obtained by dividing the force per mm width of the fabric by the mass of the fabric per unit area in g/m².

Thus, the equilibrium of forces requires that at any time during the creep test under a fixed load

\[
\sum_{i=1}^{n} \phi(\theta_i) \sigma(t) \cos \theta_i = \frac{Q}{WG}
\]

2.2 Deformation of Fibre Network

If \( \delta(t) \) is the deformation of the unit area of the network at time \( t \) after the instantaneous deformation on application of the creep load \( Q \) under the influence of load \( Q/W \) on the unit area [Fig. 2(a)], then the creep strain of the unit cell and the whole network is given by

\[
e_c(t) = \frac{\delta(t) L}{L} = \delta(t).
\]

From Fig. 2(c), strain in any fibre at an angle \( \theta_i \) to the test direction as shown in Fig. 2(c). Alternately, in this unit area (ABCD), if \( n_n \) fibres are at an angle \( \theta_n \) to the test direction, the contribution of each of the effectively contributing fibre in balancing the creep load will be \( T \sigma(t) \cos \theta_n \). The total contribution of the fibres at angle \( \theta_n \) in balancing the creep load is given by

\[
(n_n \cos \theta_n) [T \sigma(t) \cos \theta_n].
\]

2.3 Relationship between Creep Stress and Creep Strain

Creep strain in fibres depends mainly on the fibre stress, time and temperature. Under constant temperature condition, the fibre creep data can be expressed as a function of creep stress and time as

\[
e_c = f(\sigma, t).
\]

Analysis of the creep data on a number of fibres showed that for a constant stress \( \sigma \), we can relate the creep strain and time as

\[
e_c = a \ln(t) + b
\]

and constants \( a \) and \( b \) can be related to the stress level \( \sigma \) as

\[
e_c(t) = f_1(\sigma) \ln(t) + f_2(\sigma).
\]

Assuming a polynomial relationship for functions \( f_1(\sigma) \) and \( f_2(\sigma) \)

\[
e_c(t) = (a_0 + a_1 \sigma + a_2 \sigma^2 + \ldots) \ln(t) + (b_0 + b_1 \sigma + b_2 \sigma^2 + \ldots).
\]

Combining Eqs (4) and (5), we obtain the modified strain balance equation as
t. (t) \cos^2 \theta_i = f_1 (\sigma_i) \ln(t) + f_2 (\sigma_i). \quad \ldots (6)

At any given time \( t \) and an assumed value of fabric strain \( \varepsilon_i(t) \), the Eq. (6) will allow the calculation of stress levels \( \sigma_i(t) \) in fibres at different angles \( \theta_i \). These values of \( \sigma_i \) will in general not satisfy the force balance Eq. (2). By altering \( \varepsilon_i(t) \) value gradually in small steps, one can find the values of \( \sigma_i(t) \) such that Eq. (2) is satisfied. This gives the creep strain in the fabric at time \( t \). By changing the values of time \( t \) and following the same procedure, one can obtain the new value of fabric strain. In this way, one can build-up the creep curve for a fabric.

However, a simpler procedure is recommended and has been followed by relating the creep stress with the fibre creep data in the form

\[ \sigma_i = f(\varepsilon_i, t). \]

The relationship of the following type was found to be good for the experimental data

\[ \sigma_i(t) = a_0 + a_1 \varepsilon_i(t) + a_2 [\varepsilon_i(t)]^2 + a_3 t + a_4 t^2 + a_5 t \varepsilon_i(t) \cos^2 \theta_i. \quad \ldots (7) \]

The values of the coefficients \( a_0, a_1, a_2, a_3, a_4 \) and \( a_5 \) can be obtained from the creep data of the fibres.

The value of fibre stress can be substituted in Eq. (2), i.e.

\[ \sum_{i=1}^{n} \phi(\theta_i) \sigma_i(t) \cos^2 \theta_i = \frac{Q}{W G}. \quad \ldots (8) \]

The values of fibre orientation \( \phi(\theta_i) \) at different angles \( \theta_i \) to the test direction for the original fabric prior to the structural deformation can be obtained by the optical method as discussed by Hearle and Stevenson \(^1\).

2.4 Incorporation of Change in Fibre Orientation in the Model

The values of fibre orientation function obtained by the optical method mentioned above are for the fabric prior to the structural deformation. The fibre orientation in the structure would be modified due to the structural deformation on application of load, and the modification in the fibre orientation in the structure will continue with time as creep deformation occurs in the fabric. In order to take the changes in fibre orientation into account, one can update the value of \( \theta_i \) with the fabric strain.

Let us consider a segment of fibre AB originally at an angle \( \theta_i \) to the test direction as shown in Fig. 3. Let the projected length of this segment of fibre along the test direction AD be equal to \( L \) and the distance BD be equal to \( W \). Then

\[ \tan \theta_i = \frac{W}{L}. \quad \ldots (9) \]

Let us assume that at any instance during the course of the test, the length \( L \) is extended by a distance \( \Delta L \) and the width \( W \) contracts by a distance \( \Delta W \) as the fibre segment AB extends to AC and reorients itself at a new angle \( \theta_i' \) with respect to the test direction.

From Fig. 3,

\[ \tan \theta_i' = \frac{CD'}{AD'} = \frac{W - \Delta W}{L + \Delta L} = \frac{1 - \frac{\Delta W}{W}}{1 + \frac{\Delta L}{L}}. \]

Using Eq. (9),

\[ \tan \theta_i' = \left( \frac{1 - \frac{\Delta W}{W}}{1 + \frac{\Delta L}{L}} \right) \tan \theta_i. \quad \ldots (10) \]

In the above equation, the ratio \( \frac{\Delta W}{W} \) represents the total fabric strain \( \varepsilon_t \) and the ratio \( \frac{\Delta L}{L} \) represents the contraction in the transverse direction. Poisson's ratio \( \nu \) can be written as

\[ \nu = \frac{\Delta W}{\Delta L} \frac{W}{L} \quad \text{or} \quad \frac{\Delta W}{W} = \nu \frac{\Delta L}{L}. \quad \ldots (11) \]

Substituting the value of \( \frac{\Delta W}{W} \) in Eq. (10),

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Fig. 3.—Change in fibre orientation due to fabric strain.
The total fabric strain $\varepsilon_L$ consists of instantaneous fabric strain $\varepsilon_0$ on the application of load and the creep strain in the fabric $\varepsilon_c(t)$ and the Eq. (12) can be rewritten as

$$\tan \theta' = \frac{1 - \nu \varepsilon_L}{1 + \varepsilon_L} \tan \theta_0,$$

or

$$\tan \theta' = \frac{1 - \nu \varepsilon_L}{1 + \varepsilon_L} \tan \theta_0.$$

... (12)

Eq. (13) was used to update the value of $\theta_i$ as the value of creep strain $\varepsilon_c(t)$ changes. Eqs (7) and (8) are

Fig. 4—Flow diagram for obtaining the predicted values of fabric creep.
modified considering the new fibre orientation angle \( \theta' \) and can be rewritten as
\[
\sigma(t) = a_0 + a_1 \varepsilon_c(t) \cos^2 \theta' + a_2 [\varepsilon_c(t) \cos^2 \theta']^2 
+ a_3 t + a_4 t^2 + a_5 t \varepsilon_c(t) \cos^2 \theta' 
\]
and
\[
\sum \phi(\theta_i) \sigma_i(t) \cos^2 \theta' \begin{array}{c} = \frac{Q}{W} \quad \text{(15)} \end{array}
\]

The value of \( \varepsilon_c(t) \) for a given value of time \( t \) will be obtained when the Eq. (15) is satisfied using the values of \( \sigma(t) \) in the equation from Eq. (14).

An iterative procedure outlined in Fig. 4 can be developed for the above purpose. The time \( t \) is then increased and the procedure is repeated to obtain the new value of fabric creep \( \varepsilon_c(t) \). The procedure is repeated till the complete data for creep curve up to a specified time (say 1000 h) are obtained. The theoretical creep curve can then be obtained by plotting the values of fabric creep \( \varepsilon_c(t) \) against the value of time \( t \).

3 Experimental Verification of the Proposed Model

The creep study of the constituent fibres of various nonwoven fabrics was undertaken at different creep stress level\(^{14}\). The results show that the polypropylene fibres creep more as compared to the polyester fibres at the same creep load \% of their tensile strength. The creep data when plotted against the log time scale show linear relationship. This relationship shows good linear correlation for all the samples.

Fibre distribution function was obtained using a projection microscope and adopting the technique used by Hearle and Stevenson\(^1\).

The specimens of nonwoven fabrics (200 mm in width) mounted between the jaws with 100 mm gauge length were subjected to creep using single-step direct loading arrangement. Different load levels based on percentage of tensile strength obtained from the wide width tensile test were used. Fabric extension measurements were recorded at similar time interval as stated above in case of fibre test.

Creep curves of the nonwoven fabrics were obtained theoretically based on the fibre creep behaviour and structural parameters of the nonwoven fabric using the computer program developed for this purpose (Flow diagram shown in Fig. 4). The experimental values of the fabric creep were plotted on the same graph as the theoretical creep and are shown in Figs 5 and 6 for thermally-bonded and needle-punched nonwoven fabrics respectively.

Fig. 5 shows the theoretical and experimental creep curves of polypropylene thermally-bonded fabric at creep load of 25\% and 37.5\% of breaking load. The theoretical creep is higher in case of thermally-bonded fabric. While in case of needle-punched fabric, the experimental creep is higher than the predicted values. The slippage of fibres and unfolding of the pegs may be the likely reasons for this. Fig. 6 shows the predicted and experimental creep behaviour at 10\% and 25\% of breaking load for polyester needle-punched spunlaid fabric. The needle-punched fabric deforms initially giving high instantaneous strain (for example 14\% at 25\% load level) but thereafter shows very less creep strain (about 4-4.5\%) even after 1200 h.

The polypropylene thermally-bonded fabric shows lower creep compared to needle-punched nonwoven fabric particularly at low load levels up to 37.5\% of the breaking load. On the other hand, the creep in case of the polyester needle-punched fabric was low as compared to that in case of polypropylene fabric.

The prediction of creep behaviour of these fabrics using the theoretical model shows reasonable agreement with the experimental creep curves, particularly at low load levels.
4 Conclusions
A theoretical model for predicting the creep behaviour of nonwoven fabrics based on the creep behaviour of constituent fibres and their orientation in the fibre network of nonwoven fabrics has been proposed. The model is based on calculating the strain in fibres oriented at different angles to the test direction corresponding to an assumed value of fabric strain at a time $t$, obtaining the corresponding stress values in these fibres from the fibre creep data and summing up the contribution of fibre stress in balancing the applied load in the test direction. The value of the fabric creep is obtained when the contribution of fibre stress in the test direction is equal to the applied load. The procedure is repeated for other values of time $t$ till the complete data for obtaining the theoretical creep curve has been obtained. A computer program for the above purpose has been developed.

Creep curves of two spunlaid nonwoven fabrics under different creep loads have been obtained experimentally using 200 mm wide fabric samples. Experimental creep curves of these fabrics have been compared with the predicted creep curves for these fabrics using the above model. Thermally-bonded and needle-punched nonwoven spunlaid fabrics show deviation from the theoretically predicted curve although a reasonable prediction can be made about the creep behaviour of these fabrics based on the theoretical model.

References