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THEORETICAL PREDICTION OF TENSILE BEHAVIOUR OF NONWOVEN GEOTEXTILES

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ABSTRACT

A study of the tensile behaviour of nonwoven geotextiles of different structure and polymer types has been reported. The mechanical properties of the constituent fibres of these fabrics have been evaluated on the Instron tensile tester and the fabric structure has been studied using a projection microscope. Fibre network theory has been applied to theoretically predict the stress-strain behaviour of these fabrics. Tensile tests on wide width specimen have been conducted in order to evaluate the theory. In the case of thermally bonded spunlaid fabrics which have fairly strong bonds due to fusion of fibres at intersections, the theory leads to fairly good approximation. In case of needle-punched spunlaid fabrics, although there will be large deformation due to slippage at the bonding points and change in fibre orientation at the initial stage, slippage at the fibre ends which occurs due to finite length of staple fibres is not going to take place. In order to see the applicability of fibre network theory and the extent to which it can be used in the absence of a more rigorous theory, this theory has also been applied in case of needle-punched spunlaid nonwoven fabrics.

INTRODUCTION

Nonwoven fabrics for geotechnical applications are manufactured from different fibres such as polypropylene and polyester. The fibres are first laid in the form of web which is then converted into fabric by one or more of the various bonding methods like thermal bonding and needle-punching (mechanical bonding). Properties of these fabrics depend on fibre arrangement in the web, fibre properties and the bonding method used in the production of the fabric. A number of properties of these nonwoven fabrics depend on the tensile properties of the constituent fibres and the structure of these fabrics. When a fabric is subjected to a tensile load, deformation of the fabric viz. the extension of fabric in the direction of applied load and the contraction of the fabric in the transverse direction takes place. If tensile properties of the fibres and details of the fabric structure are known, it should be possible to relate them theoretically to the tensile properties of the nonwoven fabrics. A number of studies [1-12] have been reported on theoretical understanding of relationship between structure and tensile behaviour of different types of nonwoven fabrics, mainly staple fibre nonwoven fabrics.

EXPERIMENTAL PLAN

Materials

Two types of spunlaid nonwoven fabrics widely used as geotextiles viz. thermally bonded and needle-punched fabrics were selected for this study. These fabrics were of two different polymer types i.e. polypropylene and polyester of different linear densities. The details of these geotextiles are given in Table 1.

Table 1 : Details of fabrics used for studying tensile behaviour of nonwoven geotextiles

Sample Code	Filament Polymer	Linear Density (dtex)	Bonding used in Spunlaid Fabric	Mass per unit area (g/m^2)
A_F	Polypropylene	14	thermally bonded	115
B_F	Polypropylene	23	thermally bonded	203
C_F	Polypropylene	11	needle-punched & surface calendered	180
D_F	Polypropylene	11	needle-punched & surface calendered	280
E_F	Polyester	6.1	needle-punched	170
F_F	Polyester	9.6	needle-punched	220

Methods

The stress-strain characteristics of the fibres were studied on the Instron Model 4202 tensile tester after preparing the specimens of fibres removed from the selected nonwoven fabrics. Rectangular windows of 10 mm x 100 mm were cut through a chart paper and one fibre was mounted in each window using adhesive tape to prepare the specimen for testing. Fibres were tested with a gauge length of 100 mm at a strain rate of 10% per minute. A total of 40 fibre samples were tested and average stress-strain curves were obtained in case of fibres removed from each fabric.

Fabric tensile tests were carried out using wide width test method with 200 mm specimen width and 100 mm gauge length at strain rate of 10% per minute on Instron Model 4301 tensile tester. In each case, 10 tests were performed and results were averaged. The stress value in cN/tex was calculated by dividing load per unit width of sample in cN/mm by mass of fabric per unit area in g/m^2. During the tensile tests, width of the specimen at the mid-position between the jaws was noted at the fixed time intervals. Average of these values at various time interval reading were used to calculate the values of Poisson's ratio at different stages during the test.

Measurement of Structural Parameters

The various structural parameters of nonwoven fabrics were studied on projection microscope using an optical method similar to the method used by Hearle and Stevenson [1]. Magnification of 100 was used and a tracing paper having a 40 mm diameter circle marked at the centre of the paper was fitted on the screen of the projection microscope. Samples of 20 mm x 50 mm were prepared from each nonwoven fabric such that larger dimension being cut in the machine direction of the fabric. Each sample was carefully placed on a clean microscope glass slide and a few drops of paraffin liquid were added to improve the fibre definition. On focusing, fibre projections were clearly visible on the tracing paper through the screen table. A position of the slide was then chosen at random and fibres passing through the circle were traced. Different layers of the fabric were progressively focussed to examine fibre layers in turn and every time fibres projections were traced on the tracing paper as shown in Fig. 1(a). When a full traverse of the focus through the thickness of the specimen had been made, a second position on the microscope slide was chosen at random, a new sheet of tracing paper was positioned and the same process was repeated. A total of 40 such tracings were prepared in case of each nonwoven fabric. The angle of each fibre segment in the circle with respect to longitudinal direction (L) was measured as shown in Fig. 1(b). The number of fibres in each 10° segment was counted and the orièntation distribution function $\phi(\theta_i)$ defined as the ratio of the number of fibres in 10° angular segment to the total number of fibres in all the segments having mid point angle from -90° (left-side of L) to 90° (right-side of L) was obtained. The mid-point of the 10° interval was regarded as the angle θ_i, and the values of $\phi(\theta_i)$ corresponding to $-\theta_i$ and θ_i were averaged to obtain the proportion of the fibres lying at angle θ_i with reference to the longitudinal direction. Curl of a fibre segment refers to its degree of curvature, which is a factor influencing the initial modulus of nonwoven fabric. The fibre curl factor (C) was measured from the same tracings for each type of fabric as the ratio of the length of a fibre segment that spans two selected points on the segment to the shortest distance between these two points of the segment. Hearle and Stevenson [1] have explained the relationship of amount of curl in a fibre and its direction in the web for different types of nonwoven fabrics. The effect of the curl factor on the stress-strain behaviour of fabric decreases as the orientation angle θ_i with the test direction increases. Hence the average curl of the fibres oriented in 30 degree segments on either side of the test direction was considered. The actual length of fibre segments was measured using a flexible wire on the tracing of fibres. Another circle of 100 mm diameter was drawn on the tracing for this purpose. Points of intersection by line of each fibre with this circle were considered for the measurement of actual length of the fibre segment and the distance between both these points.

PREDICTION OF TENSILE PROPERTIES OF NONWOVEN FABRICS

Theory of Prediction

Fibre network theory [2] requires calculation of fibre strain corresponding to a given fabric strain, transformation of fibre strain to fibre stress and estimation of fabric stress using fibre orientation distribution function. These steps are discussed in detail below:

a) Calculation of fibre strain corresponding to a given fabric strain

As shown in Fig. 2, let OBQ be a curved fibre segment bonded at points O and Q. Let the length of fibre segment OBQ = ℓ and the length of chord OQ = k. The curl factor (**C**), the ratio of the length of fibre segment to the distance between its ends, is given by

$$C = \frac{\ell}{k} \tag{1}$$

When the strain in the fabric is large, the change in the fibre angle θ is appreciable along with the occurrence of lateral contraction which is given by Poisson's ratio ν. The fibre segment will become straight when the extension causes the chord length OD to become equal to ℓ and further fabric extension leads to strain in the fibre. For fabric extension ΔL_0, let us assume that lateral contraction is Δy and new chord length ON is equal to k′. From the geometry shown in Fig. 2

$$PQ = L_0 \tan\theta = P'Q'$$

and Poisson's ratio is given by

$$\nu = \frac{NQ' \,/\, P'Q'}{PP' \,/\, OP}$$

$$\nu = \frac{\Delta y \,/\, (L_0 \tan\theta)}{\Delta L_0 \,/\, L_0}$$

$$\nu = \frac{\Delta y}{\Delta L_0 \tan\theta}$$

$$NQ' = \Delta y = \Delta L_0\, \nu \tan\theta$$

$$\text{Fabric strain } e_F = \frac{\Delta L_0}{L_0}$$

$$\text{original length of chord } OQ = k = \frac{L_0}{\cos\theta}$$

$$\text{and original fibre length} = \ell = Ck = CL_0 / \cos\theta$$

New length of the fibre ON is given by

$$k' = \sqrt{(OP')^2 + (P'Q' - NQ')^2}$$

$$= \sqrt{(L_0 + \Delta L_0)^2 + (L_0 \tan\theta - \Delta L_0 \nu \tan\theta)^2} \tag{2}$$

$$\text{Fibre strain } e_f = \frac{k' - \ell}{\ell}$$

$$e_f = \frac{\sqrt{(L_0 + \Delta L_0)^2 + (L_0 - \Delta L_0 \nu)^2 \tan^2\theta}}{CL_0 / \cos\theta} - 1$$

$$e_f = \frac{1}{C}\sqrt{(1 + e_F)^2 \cos^2\theta + (1 - \nu e_F)^2 \sin^2\theta} - 1 \tag{3}$$

The above relation relates strain in a fibre lying at an angle θ with the fabric strain.

b) Transformation of fibre strain to fibre stress

After relating an arbitrary fabric strain e_F to the strain in a fibre lying at an angle θ to the test direction, the next step is to transform the calculated fibre strain e_f to fibre stress σ_f. At low strain levels this may be accomplished by assuming Hooke's Law between fibre stress and strain, thus

$$\sigma_f = E_f e_f \tag{4}$$

where E_f is initial modulus of the fibre.
For large strains, general relation can be written as

$$\sigma_f = f(e_f) \tag{5}$$

c) Estimation of fabric stress

In order to estimate the fabric stress in any given direction, imagine a line of unit length drawn across the fabric in a direction perpendicular to the test direction, and then consider the contribution of all fibres crossing this line. The total contribution of the fibres at angle θ to the fabric stress must be weighed according to their relative number. This is accomplished by the introduction of a fibre orientation distribution function $\phi(\theta_i)$. The relative frequency of the fibres which intersect a line of unit length perpendicular to the stress direction is $\phi(\theta_i) \cos\theta_i$. The $\cos\theta_i$ in this expression arises from the fact that the number of fibres cutting a line on the boundary of the cell is proportional to the projected length of the line perpendicular to the fibre direction.

For a fibre at an angle θ_i, the effective component of fibre stress in the test direction will be $\sigma_f \cos \theta_i$. The fabric stress σ_F is given by multiplying the effective components of fibre stress by their relative frequencies, and summing over all directions. i.e.

$$\sigma_F = \sum_{i=1}^{i=n} \sigma_f \cos\theta_i \quad \phi(\theta_i)\cos\theta_i \qquad (6)$$

After estabilishing appropriate equations (3), (4) or (5) and using the equation (6), the numerical summation gives the values of fabric stress for different values of fabric strain.

Stress-Strain Characteristic of Fibres

Average stress-strain curve for the fibres taken from each of the nonwoven fabric was obtained by averaging individual stress values from different curves corresponding to a strain value and repeating this procedure for other strain values. The average stress values were then plotted against the strain values upto the average breaking strain value. Average stress-strain curves for fibres taken from each of the six fabrics studied are shown in Fig. 3. Polypropylene filaments A_f and B_f from thermally bonded spunlaid fabrics show high extension at break and lower initial modulus. In particular, filaments from thermally bonded spunlaid fabric B_F show very high extension at break of 127% with the lowest modulus. Fibres D_f give lowest extension at break (40%) with highest initial modulus among the polypropylene fibres. Polyester filaments from needle-punched spunlaid fabrics (E_F and F_F) show relatively higher initial modulus and lower extension at break.

Prediction of Fabric Stress-Strain Behaviour

The relationship between fibre and fibre strain was obtained as

$$\sigma_f = a_0 + a_1 e_f + a_2 e_f^2 + \ldots a_n e_f^n \qquad (7)$$

where a_0, a_1, a_2, ... a_n are the coefficients, the values of which are obtained through curve fitting technique using average stress-strain curve.

The large deformation theory was assumed and the values of fibre strain in the fibres lying at different angles θ_i to the test direction were obtained. Application of this theory requires the values of Poisson's ratio. In the absence of any reliable method of theoretically estimating the Poisson's ratio in case of nonwoven fabrics, the measured values of the Poisson's ratio during the tensile tests were used. Average values of the Poisson's ratio for different structures based on past experimental data can be taken as estimated values of Poisson's ratio for the application of this theory. For a given strain level in the fabric, strain levels in the fibres of different orientations (θ_i's) were estimated, the stress-strain relationship for that fibre was utilised to obtain the stress levels in these fibres. Application of equation (6) then gives the stress-level in the fabric. Calculations are then repeated for other values of the fabric strain level and this way one can obtain the fabric stress-strain curve. A computer program has been developed for predicting stress-strain behaviour of nonwoven fabrics using the fibre network theory equations given above. Theoretical stress-strain curves of fabrics in their machine direction based on above equations have been plotted along with the experimental stress-strain curves for fabrics in the machine direction and stress-strain curves for fibres for comparison in Figs. 4 (a) to (f) for the fabrics A_F, B_F, C_F, D_F, E_F and F_F respectively.

Theoretical stress-strain curve of the thermally bonded spunlaid fabrics (A_F and B_F) plotted in Figs. 4 (a) and (b) shows good agreement with the experimental curve. This is because the fabric is thin with rigid bonds, hence network of web remains intact during the tensile test of the specimen. The initial orientation of the fibres in the network holds good to an extent during the test on this type of structure.

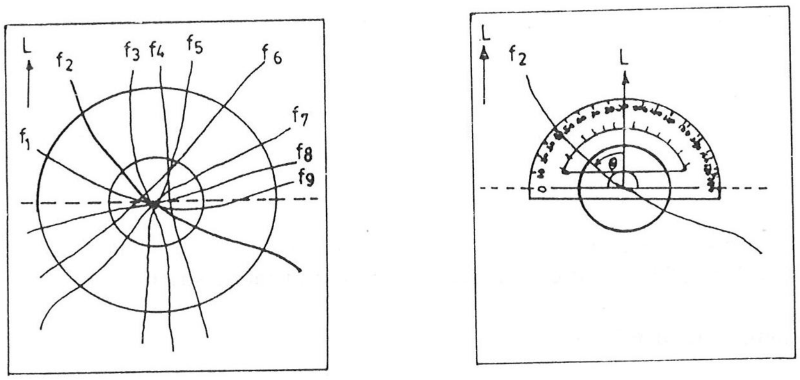

Fig. 1 Measurement of structural parameters of nonwoven fabrics
(a) tracing of fibres on the projection microscope screen and
(b) measurement of angular orientation of fibres in relation to machine direction

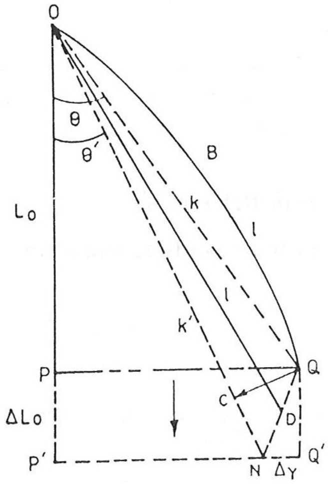

Fig. 2 Geometry relating fabric and fibre strains considering lateral contraction and change angle θ

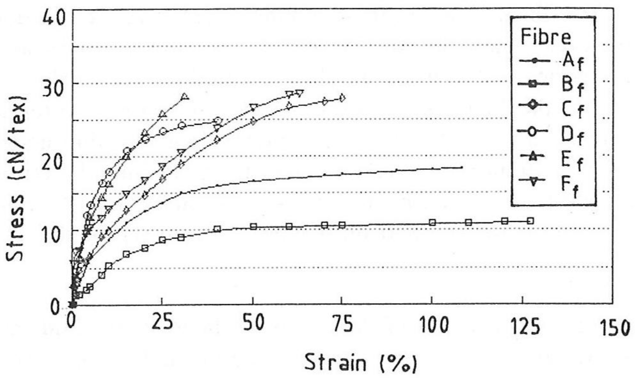

Fig. 3 Stress-strain curves of different fibres

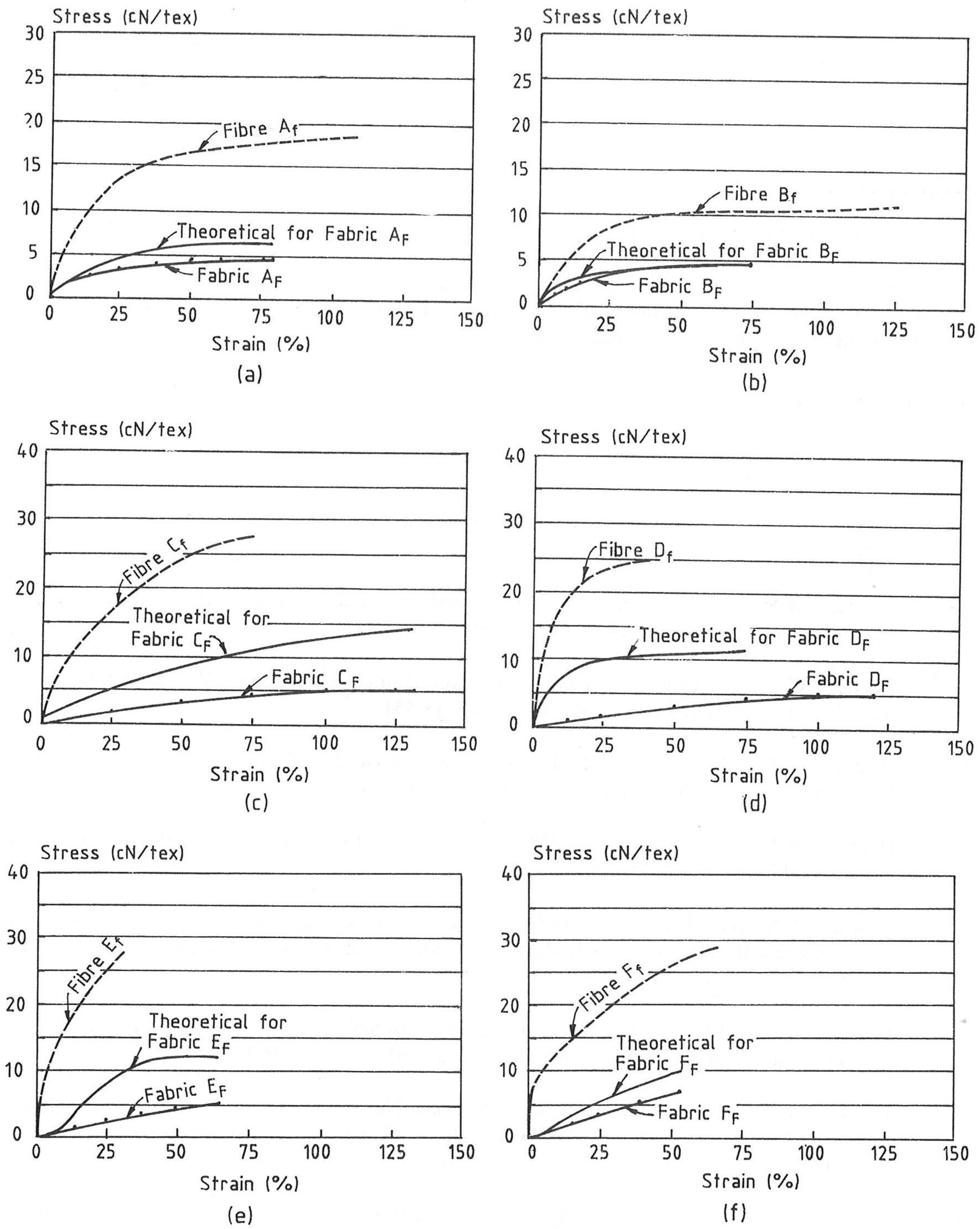

Fig. 4 Comparison of theoretical and experimental stress-strain curves in machine direction of different fabrics

Theoretical and experimental stress-strain curves of needle-punched spunlaid fabrics have been shown in Figs. 4 (c) to (f). It can be observed from these figures that theoretical curves deviates significantly from the experimental curves. The thick web of the fabric and loose frictional bonds in the structure of the needle-punched fabrics allow slippage of fibres on application of external load causing substantial extension in the fabric and reduction of the initial modulus. Fibre orientation during the course of testing also changes significantly.

CONCLUSIONS

The stress-strain behaviour of constituent fibres and the structure of fabric are the main factors which influence the mechanical properties of nonwoven geotextiles. The prediction of stress-strain behaviour using fibre network theory gives close approximation in case of thermally bonded spunlaid fabrics. However, in case of needle-punched spunlaid fabrics, the predicted stress-strain characteristics differ substantially with the experimental results.

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