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Compressibility and Hydraulic Conductivity of Geotextiles

La compressibilité et la conductivité hydraulique de géotextiles

Presently available filter design criteria differentiate between specific geotextiles in terms of their mode of construction and thickness. In this paper, three compressible geotextiles are tested in an apparatus which measures compressibility and hydraulic conductivity over a range of confining stresses. Recommendations are given for the use of the data from these tests to modify existing design criteria and so take account directly of compressibility.

Les critères actuels de la conception de filtres differencient entre les géotextiles spécifiques en fonction de leur mode de construction et de leur épaisseur. Dans cet article on soumet trois géotextiles compressibles a des essais dans un appareil qui mesure la compressibilité et la conductivité hydraulique compressée. On donne des recommandations en ce qui concerne l'emploi des données de ces essais pour modifier les critères de conception actuels, et ainsi tenir compte direct de la compressibilité.

INTRODUCTION

The introduction of geotextiles as filter drains has involved the use of materials which are very thin, sometimes compressible, and with a structure which may contain a far greater range of pore sizes than would normally occur within conventional granular drains. The use of geotextiles thus necessitates a greater appreciation of the factors which influence filter drain performance and will generally require a different approach to be adopted for their design. A joint programme of research has been undertaken by the Transport and Road Research Laboratory and the University of Strathclyde to develop such an alternative approach.

In this paper, consideration is given to the main factors which influence the filter function of geotextiles and an apparatus is described for testing their compressibility and confined hydraulic conductivity. Results obtained from tests in this apparatus, carried out on three widely differing materials, are presented and an alternative approach to the design of geotextile filter drains is suggested which includes directly the influences of the compressibility of the geotextiles.

FACTORS INFLUENCING FILTER DRAIN PERFORMANCE

Properties of the Soil

The properties of soil which have most influence on the filter function of geotextiles are their particle size distribution, shape and structural arrangement. By virtue of the above properties, the size, shape and tortuosity of the voids and flow channels through which water must pass are governed. Moreover, soils are most commonly inhomogeneous and anisotropic possessing layering, fissures and other local variations in their structure which affect hydraulic conductivity. Thus although density is sometimes used as a measure of soil structure, this property at best can only represent the average conditions within a soil which in turn may frequently have little or no value, particularly when fluid flow is dominated by only a few porous channels. In view of this inherent variability it is necessary to present soil properties in terms of an average value together with upper and lower bound values.

Properties of Geotextiles

Many of the researchers determining geotextile filter design have based their criteria on the two principal geotextile properties of pore size and permeability, (1, 2, 3, 4, 5, 6). This approach is essentially an attempt to consider the geotextile as being equivalent to a thin layer of soil. However, one problem which arises with such an approach is that of making a reliable assessment of pore size. A further difficulty is that, because of such factors as geotextile compressibility, the use of a constant permeability coefficient is not strictly valid. Further consideration of the assessment of these properties is given in subsequent sections.

Conditions of Hydraulic Flow

The conditions of flow can have a major influence on the performance of both conventional and geotextile filter drains although such affects are likely to be most pronounced with the latter types. Flow can be steady-state, transient, cyclic or reversible. Moreover, the direction of the flow with respect to the plane of the geotextile can have important consequences on its performance. Thus the selection of the appropriate geotextile for particular conditions will involve consideration of these various factors.

PORE SIZE OPENING DATA AND THEIR USE IN FILTER CRITERIA

The size of the openings in many open weave geotextiles can be directly measured, but with closely woven and non-woven geotextiles, such measurements, are not possible. For this reason, various wet and dry sieving techniques have been developed, (1, 2, 6, 7). The data obtained from these various tests are not entirely consistent, but all can provide an approximate estimate of the largest pore sizes of geotextiles in a relatively unloaded, uncompressed state. Most of the techniques produce some scatter of results from different test specimens of the same geotextile. This scatter indicates that the data on pore sizes should be presented in terms of an average value together with upper and lower bound values as described previously for soil properties. Schober and Tiendl (3) suggest a method of comparing the various filter criteria based on pore size data. They assume that the grading curve for a soil may be represented by a straight line on the usual semi-log plot, with the slope of the line being determined from the uniformity coefficient of the soil. Using this approach to normalise the filter criteria referred to previously, produces the relation shown in Fig. 1. From this figure it can be seen that the various criteria fall into two distinct groups. The first relate to woven and thin non-woven geotextiles, the second to thick non-wovens. The consistent pattern of these various criteria appears at first sight rather convincing, however as they all involve similar assumptions concerning geotextile behaviour, this may induce the trend of the results to adopt the same pattern. Moreover, it is not made clear in any of these criteria what limitations apply to the classifications for both thick and thin geotextiles. Clearly, critical factors in these limitations will be the complexity of the pore structure and the size of the filaments comprising the geotextile relative to its thickness. The former property cannot be directly measured in a simple manner but it is suggested that such properties may be assessed indirectly by considering the compressibility of geotextiles. Giroud (8) suggests that the changes in pore space may be related to compressibility in the following manner:

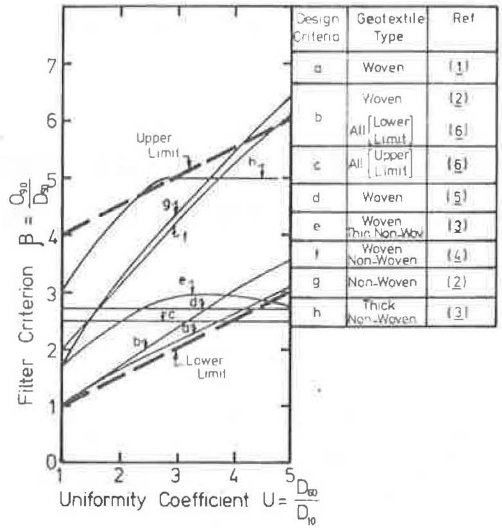
$$\frac{0 + d_f}{0' + d_f} = \frac{Tg}{Tg'} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots 1$$

Where 0 is the average pore space between filaments corresponding to thickness Tg, 0' is the average pore space between filaments corresponding to thickness Tg' and d_f is the diamter of the filaments.

Considering again Fig. 1, it can be seen that the presently available design criteria vary from that of Calhoun (1) dealing with incompressible wovens to that of Schober and Tiendl (3), dealing with very compressible thick non-wovens. If approximate upper and lower limits are placed on the various design criteria, as shown in Fig. 1, then the relationships between the filter criterion (β), which is based on unloaded pore size data, and the soil uniformity coefficient (U) can be expressed as follows:

$$\beta = 0.5\ (U + \eta) \quad \ldots\ldots\ldots\ldots\ldots\ldots 2$$

where η is a geotextile compressibility factor varying from a value of 1 for wovens to 7 for very compressible non-wovens. A need now exists to directly link this compressibility factor (η) with the measured compressibility of geotextiles.



Design Criteria	Geotextile Type	Ref
a	Woven	(1)
b	Woven All [Lower Limit]	(2) (6)
c	All [Upper Limit]	(6)
d	Woven	(5)
e	Woven Thin Non-Wov	(3)
f	Woven Non-Woven	(4)
g	Non-Woven	(2)
h	Thick Non-Woven	(3)

Fig. 1. COMPARISON OF AVAILABLE FILTER CRITERIA

REPRESENTATION OF GEOTEXTILE HYDRAULIC CONDUCTIVITY IN DESIGN CRITERIA

The most common approach is to specify the geotextile as requiring a Darcy coefficient of permeability which is some multiple of that of the soil. However, as stated previously, both the soil and the geotextile properties may vary with applied stress and it is inappropriate to attempt in general to assume a single unique value for the geotextile in order to define its relative properties. Also water flow through geotextiles is not laminar at all hydraulic gradients and confining stresses. Thus the simple proportionality relation between flow and hydraulic gradient based on Darcy's Law does not always apply. It is more appropriate therefore to assume a more general flow law for any confining stress, as follows:

$$i = bV^n \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 3$$

where i is hydraulic gradient

V is the average flow velocity through the geotextile.

b, n are constants.

Note that when flow is laminar and n becomes unity, 1/b corresponds to Darcy's coefficient permeability (k).

A difficulty of using the more general law arises because of the variations in the values of b and n with confining stress in some geotextiles, particularly with non-wovens and composites which are compressible. To overcome this, it is suggested that the hydraulic conductivity be represented as follows:

Firstly at any confining stress,

$$\frac{i_2}{i_1} = \left(\frac{V_2}{V_1}\right)^n \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots 4$$

If i_1 is taken to be unity then Eqn. 4 may be rewritten in the more general form:

$$i = \left(\frac{V}{V_1}\right)^n \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 5$$

where V_1 is the average flow velocity through the geotextile at a hydraulic gradient of unity.

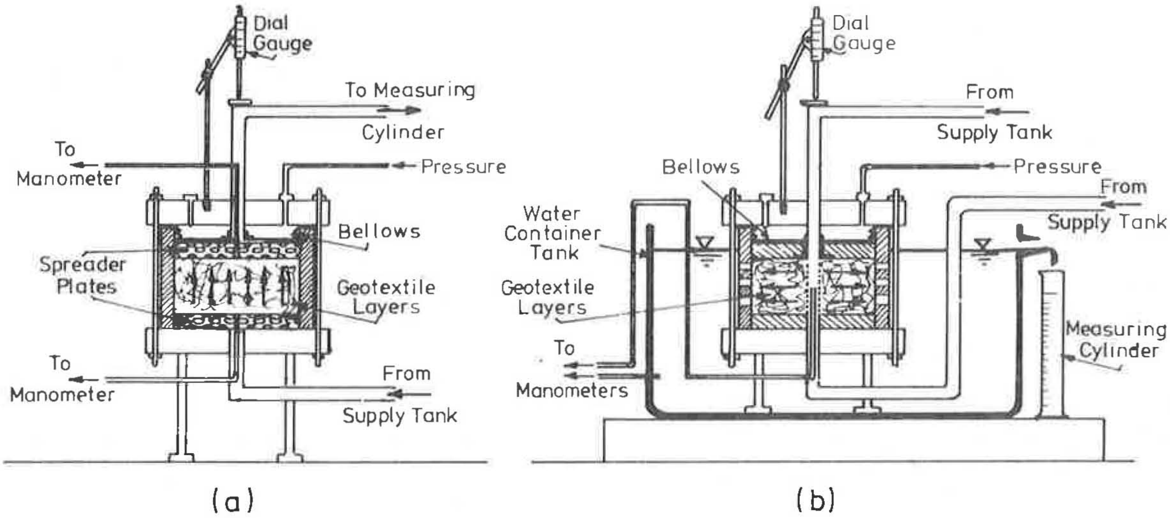


Fig. 2. LAYOUT OF TEST APPARATUS a) VERTICAL FLOW
b) RADIAL FLOW.

Now if tests are carried out at different confining stresses (σ_c) then the relationship between i and V can be calculated providing the relationships between V_1, n and the confining stress σ_c are known. Also the hydraulic gradient is related to thickness of the geotextile (Tg) as follows:

$$i = \frac{\Delta h}{T_g} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 6$$

where Δh is the applied hydraulic head across the geotextile.

With change in confining stress (σ_c) then the thickness of the geotextile (Tg) will vary. If the relationship between Tg and σ_c is known then it is possible to rewrite Eqn. 5 as follows:

$$\Delta h = T_g \left(\frac{V}{V_1}\right)^n \quad \ldots\ldots\ldots\ldots\ldots\ldots 7$$

where Tg is the thickness of the geotextile at the confining stress σ_c and corresponding to average flow velocity of V.

Inspection of Eqn. 7 indicates that if the variations of Tg, V_1 and n with confining stress (σ_c) are known then the head loss, either across or along the geotextile, can be calculated for any required average flow velocity V at any confining pressure. Since head loss is the most critical parameter in any filter design, it is suggested that this should be employed in preference to Darcy's coefficient of permeability.

APPARATUS AND PROCEDURES FOR THE MEASUREMENT OF COMPRESSIBILITY AND HYDRAULIC CONDUCTIVITY

The tests are carried out using modified consolidation cells of the type developed by Rowe and Barden (9). The cells are 152 mm internal diameter and can accommodate specimens of about 50 mm thickness. Two versions of the apparatus were developed to measure the relation between flow rate and compressibility, Fig. 2. In one version flow rates are measured across the geotextile while in the other the flow rates are measured along the geotextile in an outward radial direction. To ensure that both the flow of water and load applied to the specimen are uniformly distributed, spreader plates with 42 per cent contact area are placed on the top and bottom of the specimen, as shown in Fig. 2. The object of this test arrangement is to assess the properties of nonwoven and composite geotextiles when formed into multiple layers, however, combinations of soil and geotextile may also be used in the test apparatus. Woven geotextiles cannot be tested in this way as it cannot be ensured that their pores are aligned and that a greater degree of blocking of pore space is not occuring.

The principal modifications that were carried out on the standard Rowe cells were in relation to the inlet and outlet pipes to ensure sufficient flow and to allow the insertion of filter tips to act as piezometers. The piezometers are connected directly to external manometers to allow measurement of the applied hydraulic heads within the cell. The direct measurement of hydraulic head internallly distinguishes the design of this apparatus from those of similar design (6, 10) in which only externally applied heads were measured and assumed to be equal to the internally applied heads.

Great care was taken to control the temperature and condition of the water used in the tests. In all cases de-aired water at 20 °C was used with a dissolved oxygen content of less than 5 per cent. To reduce the suspended solid content of the water, two commercially available cartridge filters having a 1 μm opening size were inserted into the supply line between the de-aired water tank and the Rowe cells. In addition, the quantity of water flowing through the test specimens was strictly limited to generally less than 100 litres to avoid the build up of bacteria.

The test specimens were cut to the same diameter as the internal dimension of the Rowe cell. For radial flow, the specimens also had a 12 mm diameter central hole cut out. Pretreatment of the specimens involved soaking them in de-aired water for a period of one week prior to testing. They were then transferred to the Rowe cells under water. The heights of the unloaded specimens were then measured in the cells and a first load increment of 34 kN/m^2 applied. After 12 to 18 hours hydraulic flow rate tests were carried out at hydraulic gradients across the specimens of between

0.5 and 5.0. In each case the flow rate was established by measuring the time to pass 1 litre of water through the specimen or the quantity of flow passing in 8 hours, with three separate measurements made at each hydraulic gradient. The pressure on the specimen was then doubled and the flow rate tests repeated. This was continued at different pressures up to 483 kN/m^2, corresponding to the maximum available pressure supply in the laboratory.

RESULTS OF COMPRESSIBILITY AND HYDRAULIC CONDUCTIVITY TESTS

Three geotextiles were tested which are all commercially available and widely used in civil engineering works. The material chosen represent different geotextile types and are listed in Table 1 together with their basic characteristics.

The compressibility data obtained from each of the four types of geotextile are shown in Fig. 3. They are presented in terms of the relationship between the average thickness and void ration of individual layers against confining stress. The average thickness is calculated by dividing the total thickness of the test specimen by the number of layers within it. The very great difference in behaviour between the melt bonded non-woven geotextile and the needle punched non-woven and composite geotextiles is apparent between the various structural types.

The changes in average pore space (0) may be estimated from the data using Equation 1. Alternatively, compressibility coefficients may be derived from the thickness against confining stress plots thus enabling a classification of the geotextile compressibility to be made, as was suggested in relation to the filter criterion. Such classification could separate the geotextiles into various general groupings on a much more rational basis than the present "thick" or "thin" groupings. It could also allow new materials, particularly composite geotextiles to be more simply classified.

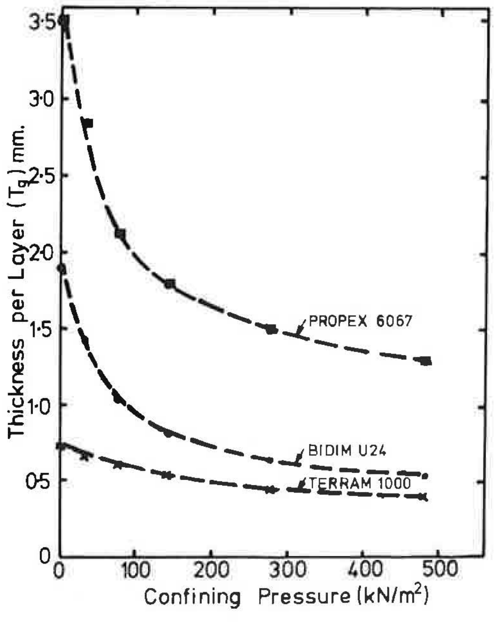


Fig. 3. COMPRESSIBILITY OF GEOTEXTILES TESTED.

Table 1. Basic Characteristics of Geotextiles Tested.

CHARACTERISTIC	TERRAM 1000	BIDIM U24	PROPEX 6067
Method of Construction	Non-woven Melt bonded filaments	Non-woven needle punched filaments	Composite Woven and needle punched
Polymer(s) Composition	67% Polypropylene 33% Polyethylene	100% Polyester	100% Polypropylene
Specific Gravity	0.9	1.39	0.91
Weight/Unit Area (g/m^2)	140	210	650
O_{90} (microns)	110	125	246
Nominal Thickness (mm)	0.7	1.9	3.5

Much work remains to be done but the technique shows considerable promise and is likely to lead to a more general approach to geotextile filter design which will allow the influence of compression to be assessed.

The data on hydraulic conductivity relating to flow across and along each of the three geotextiles studied are shown in Figs.4 and 5 respectively. The average flow velocities across the geotectiles (V_{1P}) were calculated by dividing the quantity of flow per unit time by the area of the specimen. The average radial flow velocities along the geotextile (V_{1R}) were calculated on the basis of the following equation:

$$V_{1R} = \frac{Q \ln R/r}{2\,To(R - r)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots 8$$

where Q is the quantity of flow per unit time, R, r are the external and internal radii of the specimens respectively To is the overall thickness of the test specimen at any confining stress.

The values of the coefficient n and average flow velocities across and radially along the geotextiles at hydraulic gradients of unity (V_{1P} and V_{1R}) are shown in Figs, 6 and 7 respectively. These once again clearly

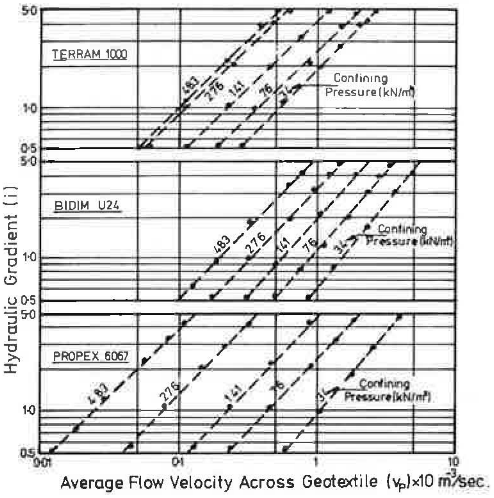


Fig. 4. RELATIONSHIP BETWEEN FLOW ACROSS GEOTEXTILES AND HYDRAULIC GRADIENT.

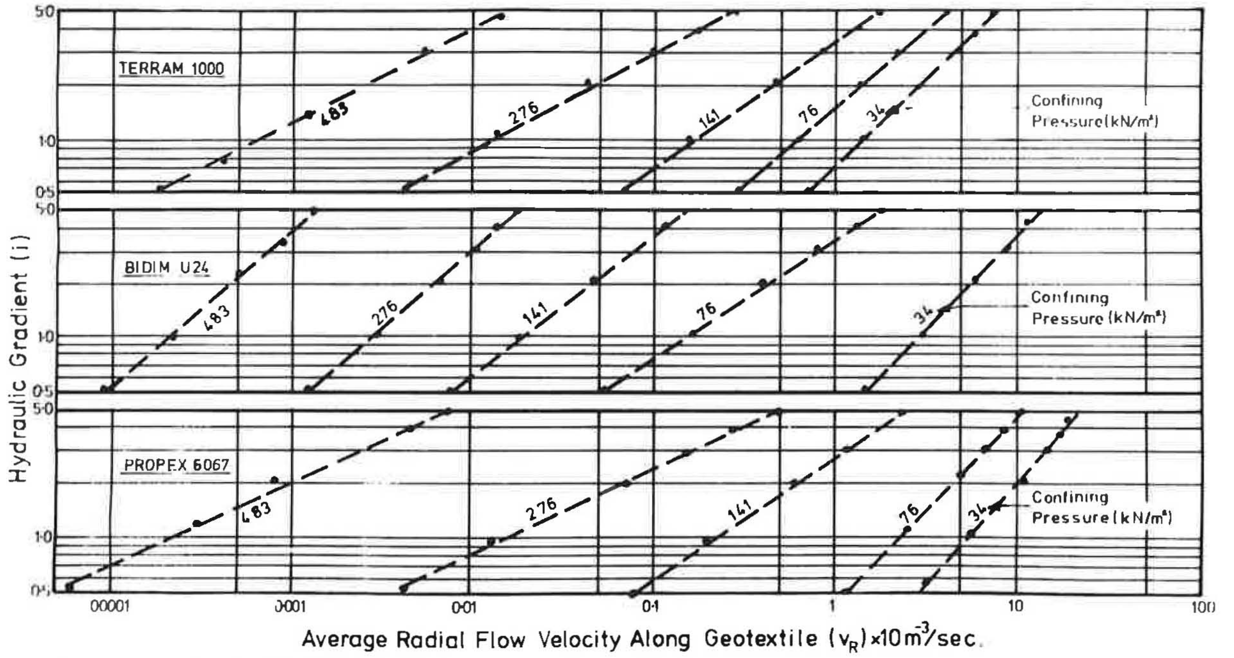


Fig. 5. RELATIONSHIP BETWEEN FLOW RADIALLY ALONG GEOTEXTILES AND HYDRAULIC GRADIENT.

Fig. 6. VARIATION IN V_{IP} and n WITH CONFINING STRESS.

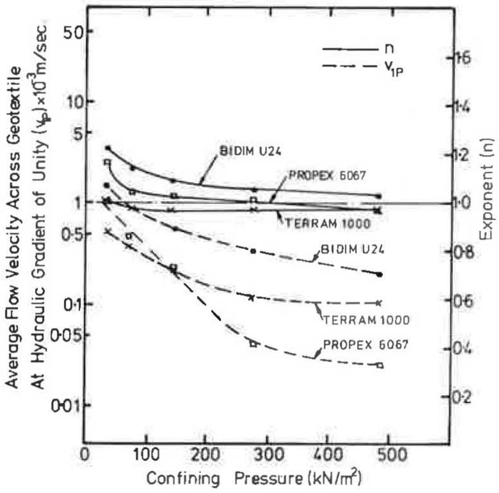
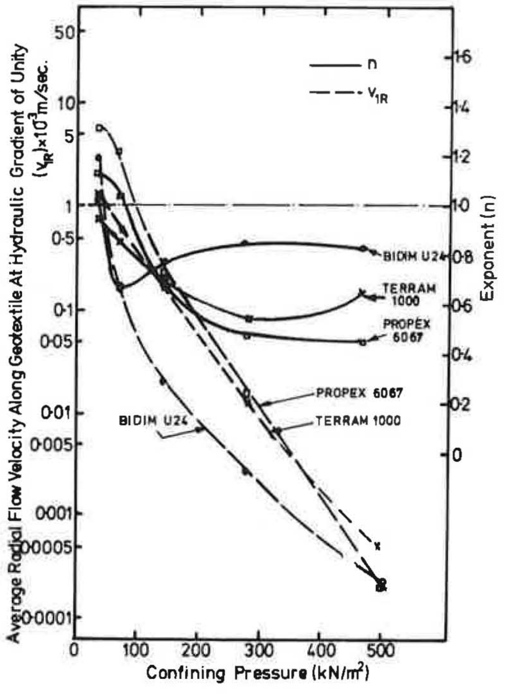


Fig. 7. VARIATION IN V_{IR} and n WITH CONFINING STRESS.



distinguish between the various types of geotextile and show that the relationship between flow capacity and confining stress is unique to each mode of construction and direction of flow. It is suggested that a measure of a geotextile compressibility would largely reflect the structural changes which are controlling its hydraulic conductivity and that this should be used to characterise their behaviour.

All the flow data indicate that n varies with confining stress for a particular geotextile subject to flow in a particular direction and confirm that Darcy's Law does not hold for these materials. The results also show that the flow velocities at hydraulic gradients of unity (V_{1P} and V_{1R}) reduce with increase in confining stress. It is suggested that it is more appropriate to characterise geotextiles by these confined flow data than by the single unloaded flow value that is presently used, since the latter is a maximum flow condition which does not relate to operational flow conditions occurring when the geotextile is compressed in-soil.

It should be noted that the value of flow at any given confining stress as obtained from these tests will not necessarily be a lower bound value since in-soil there will be clogging and blocking of the pores which are likely to further reduce the hydraulic conductivity of the geotextiles.

The values obtained from the tests with flow across the compressed geotextile can be used directly to estimate head losses (Δh) across them in preliminary design. The radial flow test data is specific to the geometry of the test specimens and cannot be generally applied to calculate head losses along geotextiles. To overcome this and to obviate the problems of side leakage, difficulty of cutting specimens as well as allow directional in-plane testing, a new version of the apparatus is being developed. It tests square specimens in undirectional flow; test data from this can be directly applied to calculate head losses in the same manner as the data from tests which flow across the geotextile. Also a single layer of geotextile may be placed in-soil and tested in the apparatus. The head losses across and along the system can be measured and related to flow in exactly the same way as is used in the present test set up. In this way, blocking and clogging effects may be measured. The new version of the apparatus will in many ways be similar to that previously developed by Fierz et al (11).

CONCLUSIONS

1. From a consideration of existing filter criteria and test data obtained from a specially modified Rowe cell apparatus, it is apparent that non-woven and composite geotextiles require a more open structure than simple woven materials for the same filter drain performance.

2. The presently available filter criteria can be simplified and modified to include the influence of geotextile compressibility.

3. The hydraulic conductivity of geotextiles should not be related to the permeability of soils using Darcy's coefficient of permeability. It is suggested that the head loss through the geotextile should be the limiting factor and this can be easily computed from a more general flow law and a knowledge of the influences of material compressibility on flow.

4. Overall the study has demonstrated that compressibility can significantly influence the filter function of geotextiles and is, moreover, an important parameter for characterising their behaviour.

ACKNOWLEDGEMENTS

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