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Inplane Permeability of Compressed Geotextiles

La perméabilité dans le plan des géotextiles comprimés

An apparatus was constructed to measure the transmissivity and thickness of geotextiles under a range of normal compressions between 2.5 kPa and 330 kPa. Water flowed radially in the plane of a ring-shaped specimen of the geotextile. Results are presented for fifteen different fabrics for the transmissivity and the derived permeability constants. The transmissivity values ranged from $5\times10^{-4} m^2/s$ for a thick needled fabric under low compression to $2\times10^{-9} m^2/s$ for a thin, compressed woven fabric. The corresponding derived permeability constants were 10^{-2} m/s to 10^{-5} m/s

Calculation of permeability constants using the channel theory developed by Fowler and Hertel gave excellent agreement for the experimentally observed values for thick, needled geotextiles.

On a construit un appareil pour mesurer la perméabilité en plan des géotextiles sous des crompressions normales entre 2.5 kPa et 330 kPa. L'eau s' écoule radialement dans le plan de l'échantillon du textile en forme d'anneau. On mesure le débit de l'eau et l'épaisseur du textile à diverses charges hydrauliques et compressions normales. On a étudié divers géotextiles y inclus des feutres aiguilletés de polyester et polypropylène, des non-tissés de liaison thermique ou chimique et des tissés de monofilaments de polypropylène.

La valeur de la transmissivité s'étend de $5\times10^{-4} m^2/s$ pour un non-tissé, aiguilleté et épais sous une compression faible, à $2\times10^{-9} m^2/s$ pour un tissé bien comprimé. Les coefficients de perméabilité correspondants sont 10^{-2} m/s et 10^{-5} m/s. De plusieurs théories pour calculer les coefficients de perméabilité pour les arrangement de fibres au hasard et d'une porosité déterminée, la théorie de canaux de Fowler et Hertel a donné des coefficients en très bon accord avec les résultats des expériences avec les non-tissés aiguilletés.

1 INTRODUCTION

Geotextiles can be considered as having two important hydraulic characteristics: The ability to transport water across the fabric, i.e. the permittivity and the ability to conduct water along the plane of the fabric, i.e. the transmissivity. The latter has received relatively little attention particularly as a function of the compression normal to the plane of the fabric. This contribution is intended to supply more information on this subject.

The transmissivity of geotextiles is of importance in many applications, not only where the transport of water by the geotextile is its primary function such as in drains in earth dams; the ability of a geotextile to transport water in its plane can also affect the performance and endurance of structures where the fabric acts primarily as a reinforcement or as a filter.

The dependence of transmissivity on the normal (compressive) forces on a fabric has been measured in the past (1) but a more comprehensive investigation seemed indicated. The present tests were designed to cover a pressure range from 2.5 kPa to 332 kPa (equivalent to 0.1m to 15m of overburden, respectively).

2 DEFINITION AND FORMULAE

2.1 Transmissibility and Inplane Permeability

The transmissivity, θ, of a fabric is a measure of the ability to transport water in the plane of the fabric and is expressed as a volume rate of flow q_{20} (referred to a standard temperature of 20°C), per unit fabric width B_g, and unit hydraulic gradient, i. Hence:

$$\theta = q_{20}/B_g \; i \; m^2/s \tag{1}$$

The transmissivity can be converted to the inplane permeability coefficient K_p if the thickness of the geotextile, H_g, is known. This results in the well known Darcy's law (2):

$$K_p = \theta/H_g = q_{20}/B_g \, H_g \; i \; m/s \tag{2}$$

If experiments are carried out at another temperature T°C then the values of q_T observed must be converted to q_{20} to allow for variations of water viscosity, η_w, which are implicit in Darcy's law.

$$q_{20}/q_T = \eta_{20}/\eta_T = 1.78/(1 + 0.0352T + .002T^2)$$

2.2 Linear and Radial Flow

The form of Darcy's law given in equation 2 describes linear flow. The present apparatus uses radial flow. It consists of a central water reservoir, a ring-shaped specimen with inside diameter d_i and outside diameter d_o. After suitable mathematical manipulation the equation for laminar, radial flow can be given as:

$$\theta = \frac{q_{20}\,(\ln d_o - \ln d_i)}{2\pi(d_o - d_i)\; i} = \frac{q_{20}\,\ln(d_o/d_i)}{2\pi\, h} \; m^2/s$$

where h = hydraulic head (m of water).

2.3 Porosity

The definition of the porosity, n, of a geotextile is analogous to that of soil: It is the volume fraction of air in the fabric and can be related to the area density, μ_g, the fabric thickness, H_g, and the volume density of the constituent fibers, ρ_f, by

$$n = 1 - \mu_g/H_g\,\rho_f$$

This quantity can also be expressed as a percentage.

3 THEORETICAL

Several theories have been proposed to calculate the permeability of fiber assemblies. They all assume a minimum fabric thickness in excess of 20 fiber diameters. Assuming in addition random distribution of fibers, the theories can be generalized as

$$K_p = (g\rho_w\lambda_f/24\pi\eta_w\alpha_f\rho_f)\ f(n) \qquad (3)$$

where α_f is a fiber shape factor and equal unity for circular fibers and f(n) is a function of the porosity, n, the form of which depends on the theory used.

For the channel theory developed by Fowler and Hertel (3)

$$f(n)_C = n^3/(1-n)^2.$$

For the drag theories of Happel (4) and Kuwabara (5) the functions are, respectively

$$f(n)_H = [4\ln(1-n)^{-1} - n(8-4n+n^2)/(2-2n+n^2)]/(1-n)$$

and

$$f(n)_K = [2\ln(1-n)^{-1} - n(2-n)]/(1-n).$$

Fig. 1 shows the shape of these three functions from n = 0.1 to n = 0.96 covering a predicted range of permeabilities of over 10^5.

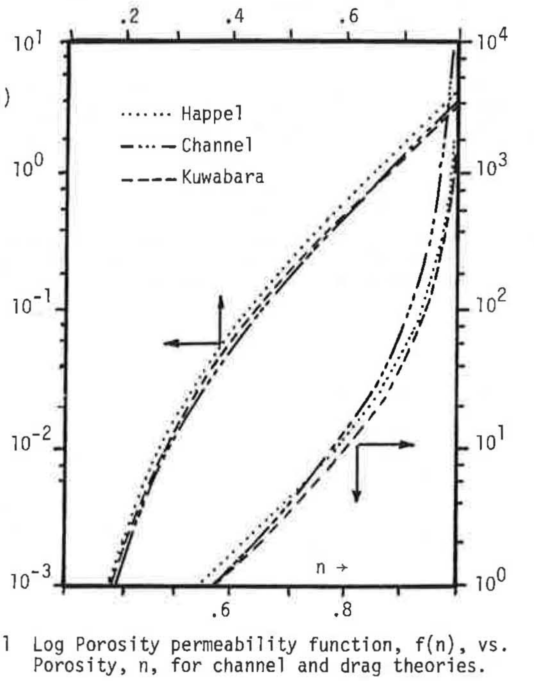

Fig. 1 Log Porosity permeability function, f(n), vs. Porosity, n, for channel and drag theories.

The region of greatest interest for geotextiles lies between n = 0.7 to 0.95 and thus includes a portion (above n = 0.85) where there are significant differences between the three theories. As will be seen the experimental data favored the mathematically simpler, channel theory.

4 EXPERIMENTAL

4.1 Apparatus

As already stated the test specimens were in the shape of a ring and a section of the specimen support is shown in Fig. 2. The geotextile, A, is sandwiched between thin rubber gaskets, B, of a similar shape and which act to form a seal against the base plate C and the upper part, shaped like a dome D. The base plate has a central access tube E containing a thermometer T and leading to manometer M (in Fig. 3).

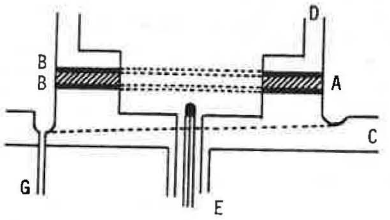

Fig. 2 Diagram of sample support and water collection groove.

Surrounding the specimen support area, the base plate has a sloping circular groove, F, which collects the water passed through the geotextile and leads it to the discharge tube G to be collected over measured time intervals.

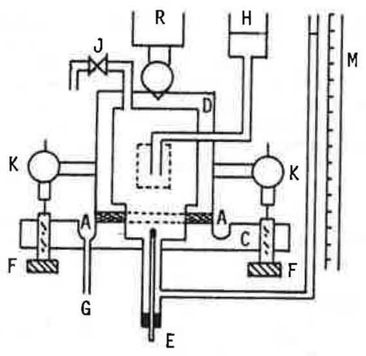

Fig. 3 Schematic of permeameter for inplane water flow.

Fig. 3 shows the complete apparatus with the upper dome having been lowered onto the specimen assembly using locating pins for better alignment. The knurled screws, F, act as adjustable anvils to the micrometers, K, which are rigidly connected to D. The micrometers are set to read zero when no fabric is between the rubber gaskets and subsequently read the fabric thickness under various compressions. They are also used as a check to assure uniform pressure application to the specimen.

Deaired water is admitted via a constant head reservoir, H, to the cavity of the dome. The water inlet pipe ends inside a diffuser to assure uniform distribution of water to the specimen. A bleed pipe and valve, J, are used to fill the cavity at the start of the run.

The compression to the geotextile is applied by means of a pneumatic ram, R, ending in a hemispherical shape which fits into a conical depression in the top of the dome. The pressure on the ram, displayed on a gauge, together with the weight of the dome and the hydraulic upthrust due to the water in the cavity, are used to calculate the compressive force on the geotextile.

The compressive stress varied from 23 kPa (when only the weight of the dome acted on the fabric) to 332 kPa when the pneumatic plunger was pressurized to 1380 kPa.

Flow readings were taken 5 minutes after any change in pressure. The water was collected over a convenient time interval (usually 60 seconds) and repeated twice. At the same time the temperature, pressure and fabric thickness were also recorded.

4.2 Geotextiles Tested

Fifteen geotextiles, obtained between 1976 and 1978 from commercial suppliers, were tested. They are listed with some of their characteristics in Table 1.

TABLE I FABRIC CONSTRUCTION AND PROPERTIES

Fabric Code +	Bond ‡	Polymer †	ρ_f kg/m^3	λ_f mg/m	μ kg/m^2	H_g *mm	n *	θX10^6 *m^2/s	K_pX10^4 * m/s
B1	N	PET	1380	9.3	.167	.68	.82	123	18.1
B2	"	"	"	9.4	.225	.93	.825	160	17.2
B3	"	"	"	9.0	.276	1.10	.825	152	13.8
B4	"	"	"	8.9	.331	1.38	.83	215	15.6
B5	"	"	"	9.4	.523	2.26	.83	410	18.1
F2	N	PP	910	7.0	.351	1.86	.79	223	12.0
CO	"	"	"	10.3	.302	1.29	.74	114	8.8
S4	"	"	"	3.5	.121	.64	.79	54	8.5
P4	B,N	PP,N	"	4.6	.143	.52	.70	11	2.0
M4	B,N	PP	"	11.8	.132	.47	.69	27	5.5
T4	B	"	"	12.5	.134	.40	.63	9	2.2
T6	B	"	"	--	.202	.51	.565	6	1.2
L8	W	"	"	--	.241	.45	.41	27	6.0
P8	W	"	"	--	.235	.43	.35	8	1.9
A1	W	PAN	980	--	.104	.30	.65	8	2.8

‡ Bonding Code: N Needled, B Heat or chemical bonding
W Woven

† Polymer Code: PET Polyester, PP Polypropylene
PAN Acrylic fiber, N Nylon

* Values given under a compression of 100 kPa

+ B1 through B5 are Bidim® (registered trade mark of Monsanto Company) nonwoven polyester fabrics

The specimens were selected at random from 1 m^2 samples and cut in a die press. The outer diameter was 108mm and the inner diameter 57mm, hence the test length in the direction of flow was 25.5mm. Most tests were carried out in quintuplicate. Reproducibility for individual specimens was less than 5% but variability between specimens was typically ±15% although this varied with the geotextile tested.

4.3 Applicability of Darcy's Law

Preliminary calculations had indicated that laminar flow was expected in the tests. This was verified experimentally by a test series at 23 kPa compression. The flow rates were varied by changing the height of the water reservoir over the range of 20mm to 1 m. The 5 polyester fabrics and 6 polypropylene fabrics of various thicknesses and constructions were tested. In all cases the results showed good linear behavior. The correlation coefficients were all 99.9% or greater and the flow axis intercepts lay within $\pm 0.2 X 10^{-6} m^3/s$ thus confirming within experimental error that Darcy's law was applicable.

Subsequent tests were carried out at a constant hydraulic head of 300mm of water, so that the transmissivity was related to the volume flow (corrected to 20°C) by:

$$\theta = 3.374 \times 10^{-7} \; q_{20} \; m^2/s.$$

4.4 Supplemental Tests Under Very Low Compression

Because of the large weight of the apparatus described earlier it was decided to build an alternate lightweight head to do additional runs at much lower fabric compressions. The compressive stress in this tester was 2.52 kPa and the tests were carried out under a falling head mode with time and volume readings being taken at intervals of 25mm hydraulic head from 356mm to 105mm. These readings were temperature corrected and appropriately transformed for the different geometrical arrangement and the transmissibility calculated. These readings were well in line with the trends observed in the constant head apparatus and are included in the following plots.

The fabric thickness was not measured during these low compression permeability tests but calculated from independent thickness measurements under various compressions.

4.5 Transmissivity Measurements

The experimental results of 5 different test specimens are plotted in Fig. 4 and show the decrease in transmissivity of the family of needled polyester geotextiles. They were produced by the same manufacturing process and only differed in their area density (mass per unit area). Under lower compressions the transmissivities were in the order of the area densities, but at higher compressions some divergencies were observed. These differences lay within specimen to specimen variations and are therefore not unexpected.

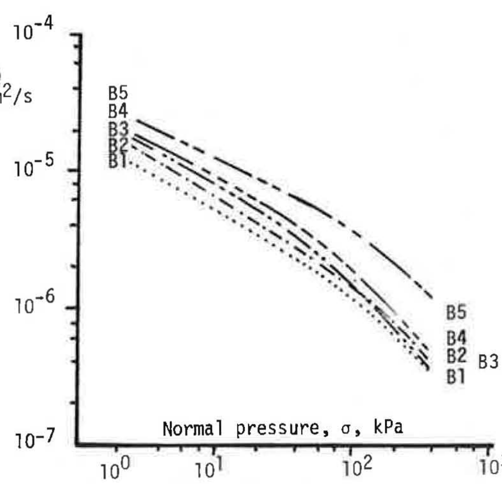

Fig. 4 Log Transmissivity, θ, vs. log normal pressure, σ, for needled polyester geotextiles.

Fig. 5 shows the corresponding plot for the group of needled and bonded polypropylene fabrics and the woven geotextiles. The needled polypropylene fabrics are very similar to the needled polyester fabrics but the transmissivities tend to decrease somewhat more rapidly at higher compressions. Some of the other fabrics showed some surprising trends. The woven fabrics P8 and L8 were of similar structure, construction, appearance and transmissibility at low compression. However at higher compressions they differed by a factor of 30. Neither of these materials nor the geotextiles designated A1, P4, T4, T6 can be considered suitable as drainage geotextiles. M4 and S4 are of intermediate transmissivity at low compressions but must be included in this list of unsuitables, especially at higher compressions.

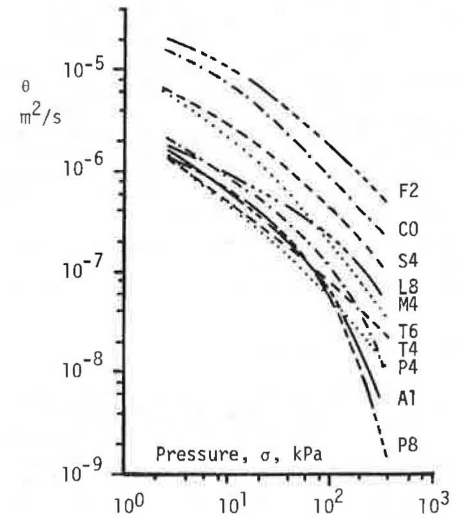

Fig. 5 Log Transmissivity, θ, vs. log normal pressure, σ, for polypropylene and woven geotextiles.

The fabrics best suited for transporting water in their plane are thick, needled fabrics with area densities of .250 kg/m^2 or higher.

As Figs. 4 and 5 also show, the decrease in transmissivity tends to be more gradual for lower compressions but accelerates as the pressure are increased. It is therefore advisable when estimating transmissivities for pressures beyond those for which experimental data exist to allow for this factor.

Over the range of normal compressions tested the transmissivity decreased to less than 10% of the low compression value for all fabrics. In one case it dropped to less than 0.2%.

4.6 Fabric Thickness under Pressure

When using geotextiles as a drain the value of the transmissivity of the fabric under the anticipated compressions is the most important parameter for the geotechnical engineer. However, the value of the permeability of the geotextile can be used to gain insight into the behavior of fabrics. It has been possible to link it to theories using fabric properties easily measured and which may make extensive hydraulic testing of new fabrics unnecessary. A few key tests can then be extrapolated beyond the range of experiments and yield reasonably assured estimates.

The thickness of fabrics was measured under two different conditions: One series was measured wet in the permeability test as already indicated. In another series the polyester fabrics were tested dry in a compression tester. Fig. 6 shows the two series combined as there was no significant difference between the two when the slightly different area densities of the samples were taken into account.

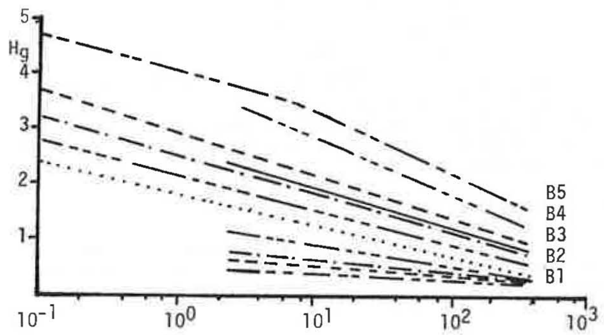

Fig. 6 Thickness of geotextiles, H_g vs. log normal pressure, σ.

On the basis of the thickness tests the porosity of the geotextiles was calculated and as Fig. 7 shows it decreased as the pressure was increased. The B family of fabrics showed a range of porosities from .906 to .946 at 500 Pa (the pressure recommended by ASTM for thickness measurements of geotextiles). At this pressure the thinnest fabric was also the most porous. At the highest pressure measured the porosity had decreased to .748 to .772 with the thickest fabric showing the highest porosity.

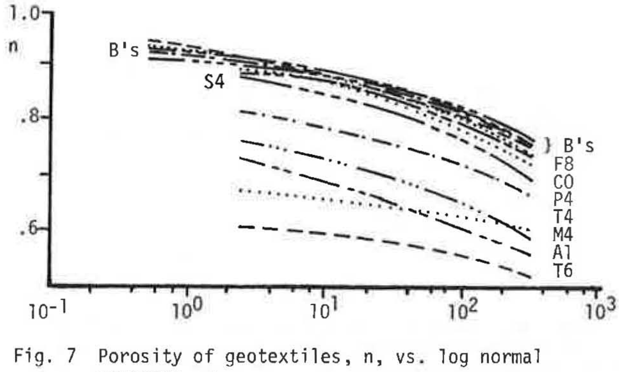

Fig. 7 Porosity of geotextiles, n, vs. log normal pressure, σ.

The concept of porosity for woven or very thin, compressed nonwoven fabrics is not really appropriate but included here to show how the properties of geotextiles are quite gradual and any statement of cut-off between porous and nonporous fabrics is to some extent arbitrary.

4.7 Inplane Permeability Constants

The values of transmissivity shown in Figs. 4 and 5 divided by the thickness of the fabric at the same normal pressure yield the value of the inplane permeability constants. They are shown in Fig. 8. They can be seen to cover a narrower range than the transmissivity values since both the thickness as well as the porosity of the fabrics decrease with pressures.

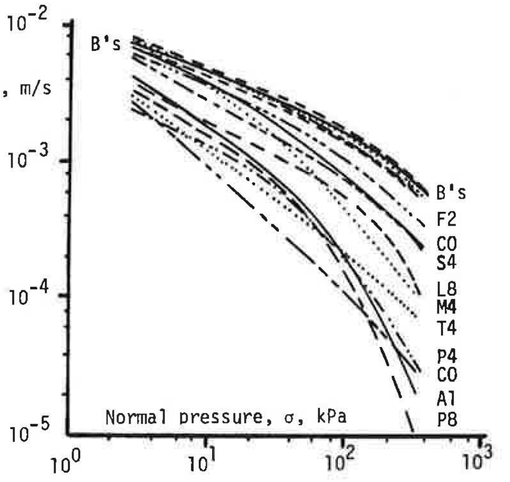

Fig. 8 Log permeability constant K_p vs. log normal pressure, σ for geotextiles.

The needled polyester fabrics are essentially independent of the area density of the fabric, which merely indicated that the structure of these fabrics was very similar and not affected by the thickness. This fabric group showed the highest permeability constants. The values of the needled polypropylene fabrics F8, CO and S4 were similar at low compressions but decreased more rapidly with pressure. Most of other fabrics were significantly less permeable at all pressures, and the differences increased with higher compressions.

Typical values for permeability constants for normal pressures of 100 kPa are listed in Table I, others will be found in the next section.

4.8 Comparison with Theory

The extensive data available on the needled polyester geotextiles were used to test the relative fit of experimental data with the three theories discussed in section 3. To this end the derived values of f(n) were compared to the values of $f(n)_C$, $f(n)_H$ and $f(n)_K$. From equation (3)

$$f(n) = (24\pi n_w \lambda_f / g \rho_w \lambda_f) K_p = A\, K_p$$

the factor A can be calculated from the data contained in Table I. Fig. 9 shows the points for the thick needled fabrics: the needled polyesters and polypropylenes F8 and CO. The fit with the channel theory is excellent for the polyesters and F8 and not unsatisfactory for CO. The latter shows a significant deviation from the theory but the fit with the channel theory is better than for the drag theories.

From this evidence the channel theory was used to calculate permeability constants for several of the nonwoven geotextiles tested. They are shown in Table II and illustrate that the fabrics M4, T4 and T6 are too thin for the theory to be appropriate. Fabrics S4 and P4 also show significant deviations which may be due to their non-uniformity of structure.

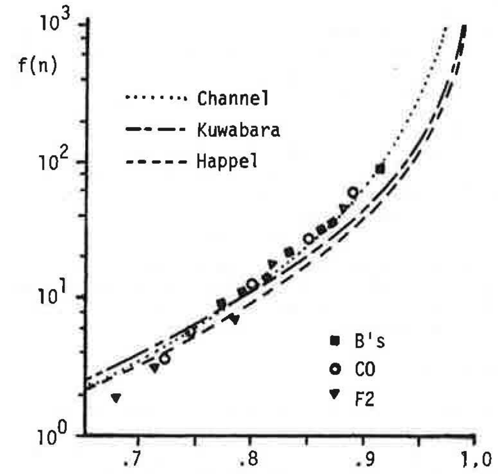

Fig. 9 Log porosity permeability function, f(n) vs. porosity, n. Theory and from experiments.

TABLE II EXPERIMENTAL VS. CALCULATED PERMEABILITY CONSTANTS

Fabric	Experimental/Calculated, K_p, 10^{-4}m/s at: σ = 2.52 kPa	σ = 23 kPa	σ = 137 kPa	σ = 332 kPa
B1	75.5 / 103.5	32.1 / 27.1	13.2 / 10.9	6.8 / 5.7
B2	83.8 / 90.7	30.4 / 27.1	12.3 / 10.9	6.2 / 6.8
B3	76.9 / 78.9	33.8 / 33.0	14.3 / 11.9	7.3 / 6.8
B4	68.2 / 90.7	31.2 / 33.0	12.6 / 11.9	6.4 / 8.0
B5	64.4 / 86.0	32.7 / 33.0	12.9 / 11.9	6.6 / 8.0
F8	59.2 / 58.3	25.5 / 27.3	8.1 / 10.0	3.9 / 5.0
CO	64.2 / 77.4	24.5 / 36.3	5.7 / 10.6	2.7 / 4.7
S4	54.7 / 28.8	18.1 / 15.8	6.1 / 4.9	2.5 / 1.8
P4	24.7 / 15.8	8.7 / 5.3	1.4 / 3.3	0.3 / 2.0
M4	83.2* / 13.4	20.0* / 7.0	3.2 / 3.8	1.2 / 2.3
T4	31.1* / 5.7	6.4 / 4.7	1.7 / 3.4	0.8 / 2.7
T6	26.8* / 2.9	4.3 / 2.5	0.8 / 1.8	0.3 / 1.4

* Suspected inadequate seal between rubber gasket and specimen

5 SUMMARY AND CONLUSIONS

These tests on the transmissivity and inplane permeability constants showed that for thick, bulky (needled) fabrics the observed values agreed remarkably well with those calculated from the channel theory developed by Fowler and Hertel. The theory, being based on the assumption of complete (3 dimensional) istropy of the fiber arrangement will therefore predict the same permeability constant for water moving normal to the fabric plane. Within 20 per cent that appears to be the case for values reported for B-3 (1).

The theoretical development shows that if the fabric porosity and the fiber shape, linear and bulk densities are known, then the permeability and hence the transmissivity and permittivity can be calculated.

For bulky fabrics that use binders or have significantly nonisotropic or non-uniform construction the theory may still yield a useful approximation but must be used with great caution. It may give an upper or lower limit to actual permeabilities depending on the nature of deviation from assumed structure.

The transmissivity of thin fabrics is so low that the drainage function of such geotextiles is essentially negligible and correspondence with this or any other theory is of no interest to the design engineer.

ACKNOWLEDGEMENTS

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REFERENCES

(1) Bourdillon, M. et al , Utilization of Nonwoven Fabrics in Drainage , C. R. Coll. Int. Sols. Textiles, p 279, Paris, 1977.

(2) Scheidegger, A. E., The Physics of Flow Through Porous Media, U. of Toronto Press (1963).

(3) Fowler, J. L., Hertel, K. L., Flow of a Gas Through Porous Media, J. Appl. Phys. 11, 7, 496, 1940.

(4) Happel, J., Viscous Flow Relative to Arrays of Cylinders, A.I.Ch.E., 5, 2, 174 (1959).

(5) Kuwabara, S., Forces on Randomly Distributed Cylinders in Viscous Flow, J. Phys. Soc. Japan, 14, 4, 527 (1959).