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Hydraulic Conductivity of Geotextiles under Typical Operational Conditions

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ABSTRACT

It is well known that granular backfill can account for more than 50% of the total construction cost for typical geosynthetic-reinforced soil structures. It is therefore desirable to investigate the possibility of using low-quality on-site soil, which may be cohesive and near saturated, as backfill. A geosynthetic that possesses adequate drainage capability in addition to having high tensile stiffness and strength would be highly suitable for this purpose. This study was conducted to investigate the cross-plane and in-plane hydraulic conductivities of such geotextiles under typical operational conditions. Two types of geotextile, namely, a nonwoven and a woven–nonwoven composite geotextile, were tested by using different methods of confinement in their virgin state. Samples of the geotextiles retrieved from the field were also tested, and the results were compared with the hydraulic conductivity of virgin specimens. An equation is proposed to include the effect of confining stresses on the hydraulic conductivity of geotextiles. A reduction factor, termed the degree of retention (DOR), is introduced to *express the long-term reduction in hydraulic conductivity due to soil-particle retention. In addition, a simple performance test is proposed for investigating the flow behavior of a soil–geotextile composite under its typical operational conditions.*

NOTATION†

b	Slope of i versus v curve (s/cm)
b_0	Value of b at zero effective normal stress (s/cm)
d_{50}	Mean diameter of soil (mm)
d_{85}	Diameter of soil corresponding to 85% finer (mm)
DOR	Degree of retention (%)
E_{ci}	Initial modulus of compression in thickness direction of geotextile (kgf/cm^2)
e	Void ratio
h	Head loss (cm)
i	Hydraulic gradient
i_0	Threshold hydraulic gradient
k	Coefficient of hydraulic conductivity (cm/s)
k_0	Value of k in unconfined condition (cm/s)
k_h	Coefficient of in-plane hydraulic conductivity (cm/s)
k_n	Coefficient of cross-plane hydraulic conductivity (cm/s)
L	Length of flow path, length of geotextile (cm)
m_f, m_s	Mass of geotextiles and soil per unit area (g/cm^2)
n	Number of sheets of geotextile
q	Flow rate (cm^3/s)
Q	Quantity of discharge (cm^3)
S	Rate of increase in b with confining stress (cm.s/kgf)
T	Load per unit width of geotextile in axial direction (tf/m)
t_g	Thickness of geotextie (cm)
t_{go}	Initial thickness of geotextile (cm)
v	Flow velocity (cm/s)
W	Width of geotextile (cm)
β	Coefficient to indicate rate of decrease of k with confining stress (cm^2/kgf)
ε	Tensile strain in the axial direction of geotextile
ε_n, ε_{ult}	Compressive and ultimate value of compressive strain in thickness direction of geotextile
θ	Transmissivity (cm^2/s)
ρ_f, ρ_s	Density of fiber and soil (g/cm^3)

† Exceptionally, units of kgf have been used instead of SI units due to the calibration of the test equipment.

σ'_n Effective normal stress (kgf/cm^2)
ψ Permittivity (s^{-1})

1 INTRODUCTION

Soil is inherently strong in compression and shear, but weak in tension. In recent years, the technique of reinforcing soil structures by incorporating geosynthetics that possess much higher tensile stiffness and strength than soil, and the capacity to bond with soil through friction/adhesion, has gained increasing applications in geotechnical engineering practice. In general, geosynthetics are more economical, more easily handled and constructed, and more resistant to corrosion and bacterial action than many traditional materials, including metals.

The backfill in geosynthetic-reinforced soil structures is traditionally granular soils. In nearly every existing design method for such structures, cohesive soils have been precluded from being used as the backfill. This is mostly because cohesive soils are likely to have low bond strength with the geosynthetic and because some cohesive soils may generate a high excess pore-water pressure and experience a large amount of deformation when subject to variation in moisture content or upon the application of external loads. Nevertheless, since the cost of granular backfill can often be as high as 50% of the total cost when granular soils are not readily available (Mitchell & Villet, 1987), the use of on-site soils, even near-saturated cohesive soils, in the construction of embankments and retaining walls has yet to be attempted.

The Transportation and Road Research Laboratory in the UK (Boden *et al.*, 1978) and the University of Alberta and Alberta Transportation (Scott *et al.*, 1987) performed full-scale tests involving the use of cohesive backfills. They reported that the earth structures suffered from a large amount of deformation and a high excess pore-water pressure. It should be noted, however, that the reinforcements used in these tests, which were metallic/plastics strip and geogrid, respectively, had little filtration/drainage capability.

Tatsuoka *et al.* (1986, 1991), through a series of field tests, demonstrated the effectiveness of using a nonwoven geotextile with filtration/drainage capability for reinforcing earth embankments constructed with a volcanic silty clay called Kanto Loam. The grain-size distribution and index properties of Kanto Loam used in this study are shown in Fig. 1 and Table 1, respectively. The Kanto Loam in the four full-scale geotextile-reinforced embankments (of heights ranging from 4 to 5·5 m), as reported by Tatsuoka *et al.* (1986, 1991), had a degree of saturation of 83–90% and the as-constructed water content was 100–120%. However, these test

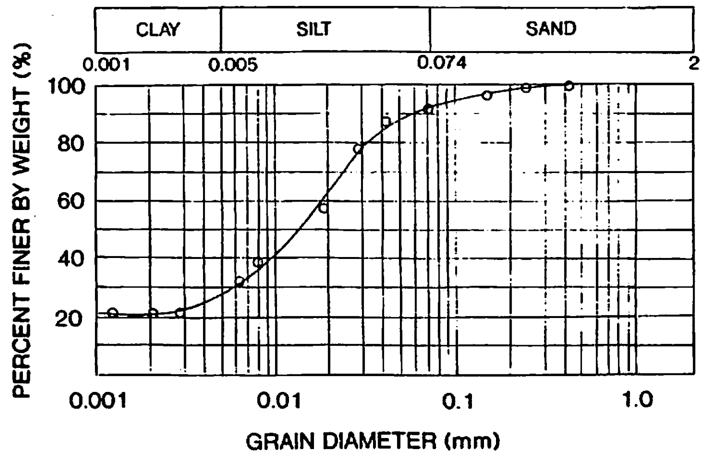

Fig. 1. Particle-size distribution of Kanto Loam soil.

TABLE 1
Index Properties of Kanto Loam

Dry unit weight	: 0·52 kgf/cm^3
Specific gravity	: 2·9
Mean diameter, d_{50}	: 0·0145 mm
Particle diameter corresponding to 85% finer, d_{85}	: 0·04 mm
Natural water content	: 120%
Liquid limit	: 168%
Plastic limit	: 115%
Plasticity index	: 53
Coefficient of hydraulic conductivity	: 10^{-6}–10^{-7} cm/s

embankments have performed satisfactorily ever since they were constructed several years ago, even though they have been subject to many heavy rainfalls and earthquakes.

Figure 2 shows the variation in pore pressure in one of the test embankments of height 5·2 m during a heavy rainfall in June 1984. When the rainfall occurred, the geotextile-reinforced zones at both sides of the embankment were able to maintain a high degree of suction (negative pore pressure), whereas positive pore pressure was generated in the unreinforced zones as water infiltrated into the soil. After the rainfall, the excess pore pressure dissipated rapidly through the geotextile. This case history clearly illustrated the importance of the filtration/drainage capability of a geosynthetic for reinforcing earth structures with cohesive backfill. A rational design procedure for geotextile-reinforced soil structures with cohesive backfill must therefore take into account the hydraulic behavior of the geotextile.

This paper presents the results of a comprehensive study investigating the cross-plane and in-plane hydraulic conductivities of geotextiles under operational conditions typical for reinforced soil structures. Two types of

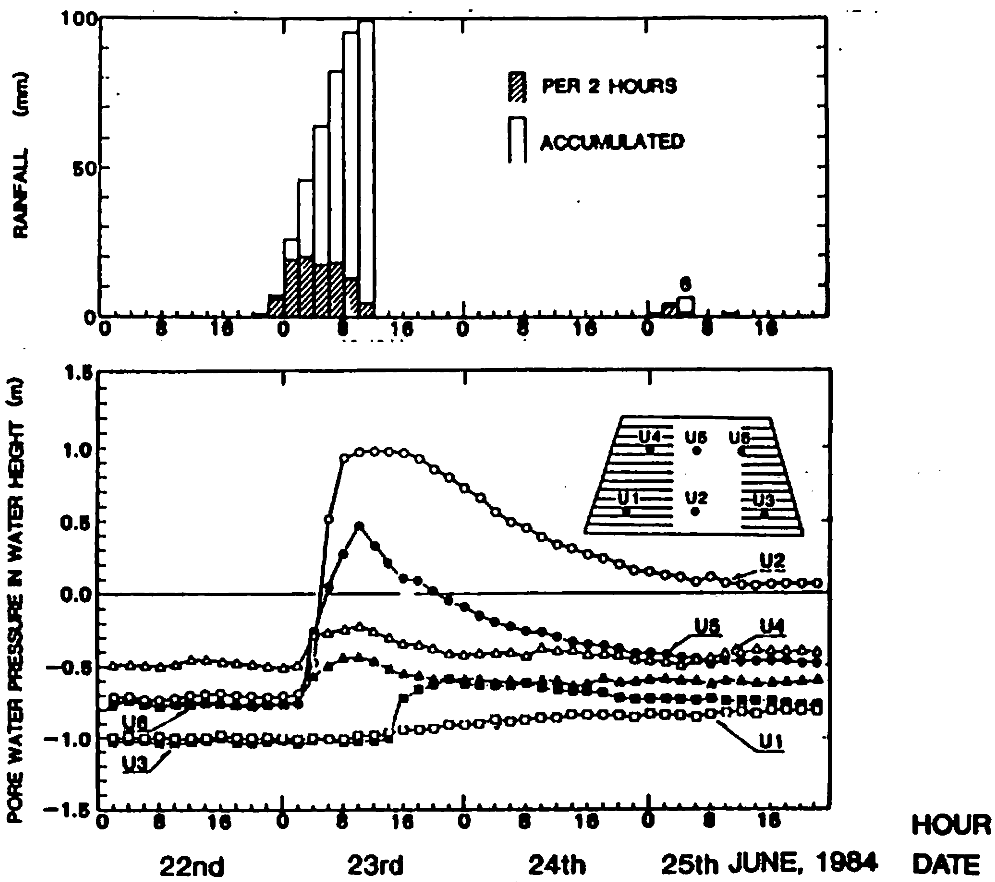

Fig. 2. Variation of pore pressure in test embankment during rainfall (after Tatsuoka and Yamauchi, 1986).

geotextile were tested by means of a newly developed testing device. Different methods of stress confinement were examined. Samples of geotextiles retrieved from the field were also tested, and the results were compared with the hydraulic conductivities of virgin geotextile specimens tested under identical conditions. On the basis of the test results, an equation is proposed to include the effect of confining stress on the hydraulic conductivity of a geotextile and a reduction factor, termed the degree of retention (DOR), is introduced to account for the long-term effect. In addition, a simple two-dimensional performance test is suggested for investigating the flow behavior of a soil–geotextile composite under typical operational conditions in earth structures.

2 FEATURES OF PERMEABILITY-TESTING SYSTEM

The testing system (Fig. 3) is composed of four basic components: a water-supply tank, a water-receiving tank, a permeameter, and a measuring system. The details of this testing system are presented elsewhere (Ling,

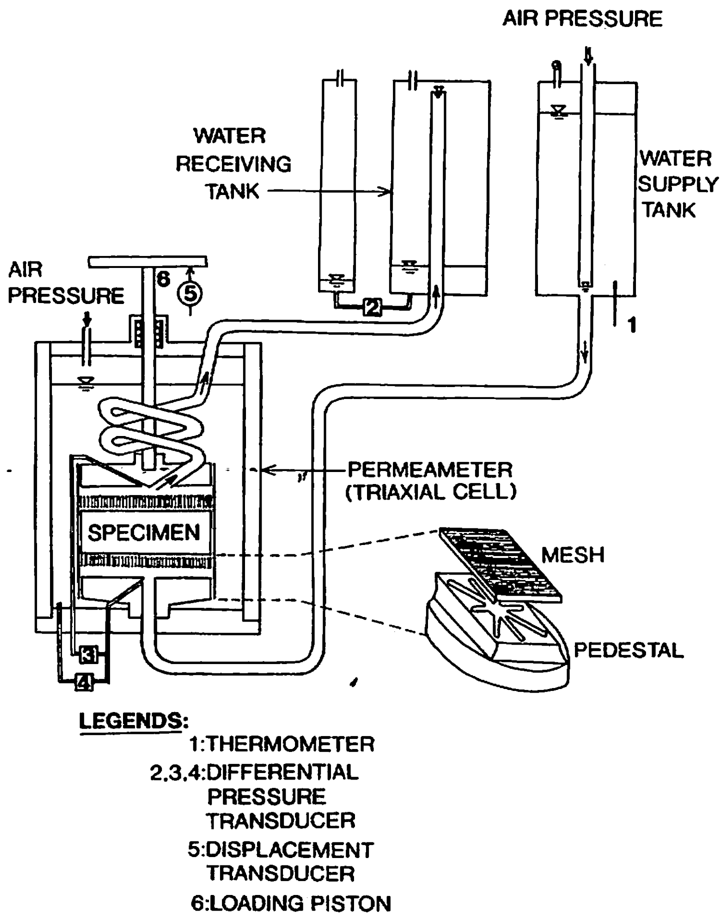

Fig. 3. Automated permeability-testing system.

1990; Ling *et al.*, 1990). The system has the following unique features as compared with most types of conductivity-testing apparatus.

(i) In this device, the constant head is achieved by applying a prescribed air pressure through the tip of a tube located near the bottom of the water-supply tank (a Mariotte bottle) and by making water leave the outlet of a tube standing in the water-receiving tank at atmospheric pressure. Back pressure can be applied on the specimen if desired.

(ii) Tests of different types of flow behavior (cross-plane flow, in-plane flow, and flow in a soil–geotextile composite) can be performed by using the same apparatus; the possible discrepancies due to the use of different types of apparatus for different types of test, was therefore avoided.

(iii) For the cross-plane-flow test, the apparatus not only allows the load to be uniformly applied on the plane of the geotextile but at the same time allows the water to be evenly distributed over the entire plane. These features are accomplished by using a rigid mesh lined with densely spaced metal strips (Fig. 3).

(iv) The apparatus can be used for measuring the hydraulic conductivity of a soil–geotextile composite in an anisotropically consolidated condition by applying a deviatoric load through the piston rod (denoted by 6 in Fig. 3) while keeping the composite confined with a rubber membrane under pressurized cell water.

(v) The head loss in the geotextile specimen is measured at locations very close to its plane by using a differential-pressure transducer (denoted by 3 in Fig. 3). The head loss of the apparatus between two measuring points at different flow velocities had been calibrated beforehand so that the actual head loss in the specimen could be readily obtained. This also ensures that the apparatus is not controlling the flow behavior. The details of the calibration have been presented by Ling (1990).

(vi) Leakage of water along the edges of the geotextile, particularly for the in-plane flow, is avoided by confirming the geotextile specimen with a flexible membrane, as in the triaxial test of soil.

(vii) The effective normal stress, instead of the total normal stress, is measured, since the excess pore-water pressure in the geotextile specimen is not zero. The difference in effective normal stresses at the two ends of a specimen has been found to be negligibly small when compared with the range of effective stress considered in this study. Hence, only the effective stress at one end of the specimen was measured with a high-capacity differential-pressure transducer (denoted by 4 in Fig. 3).

(viii) To achieve better test accuracy and test repeatability, all the physical quantities in this testing system were measured at selected time intervals by using electronic transducers. For instance, the quantity of discharge was obtained by measuring its height in the water-receiving tank by means of a low-capacity differential-pressure transducer (denoted by 2 in Fig. 3).

3 DESCRIPTION OF GEOTEXTILES

Three different geotextiles were tested in this study: a spunbonded needle-punched polypropylene-fibre nonwoven geotextile, a woven–nonwoven composite geotextile, and spunbonded needle-punched polypropylene-fibre nonwoven geotextile retrieved from a test wall two years after installation. The composite geotextile had a layer of polypropylene-fibre woven geotextile interbedded between two layers of spunbonded needle-punched polypropylene-fibre nonwoven geotextile as shown in Fig. 4. In

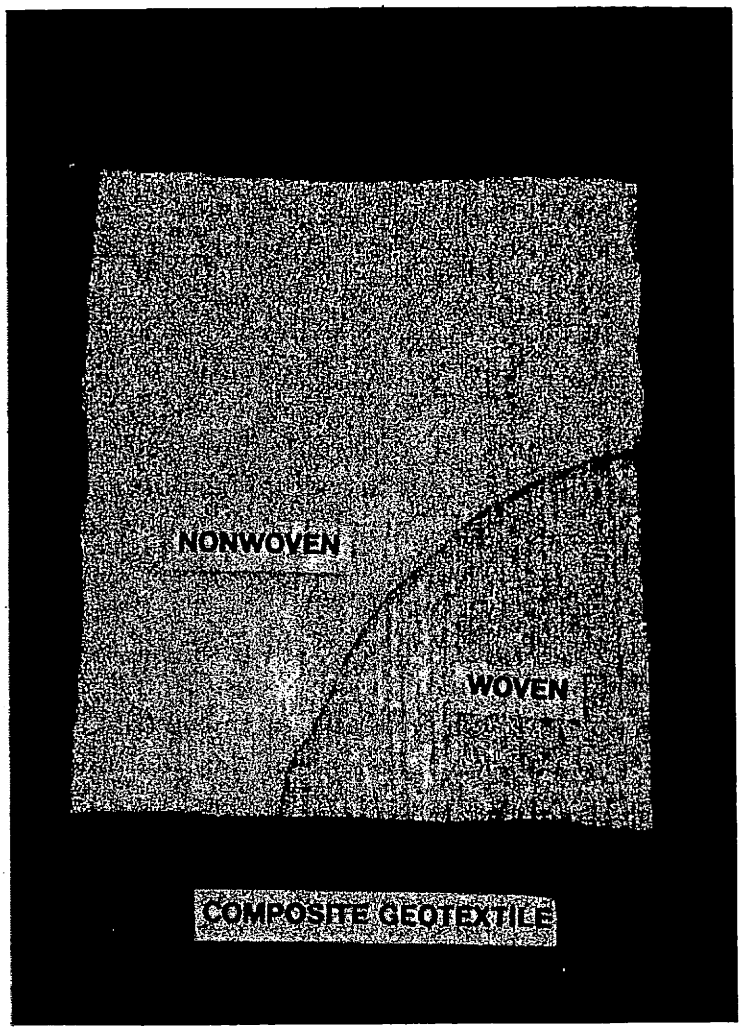

Fig. 4. Composite geotextile.

this paper, these geotextiles are referred to as the nonwoven, the composite, and the retrieved geotextiles, respectively. The mass per unit area, the thickness, and the apparent opening size (ASTM D 4751) of these three geotextiles are given in Table 2. Note that the retrieved geotextile had a different mass per unit and thickness from the virgin nonwoven geotextile. The polypropylene fiber used to manufacture these geotextiles has a density of 0·91 g/cm^3 and an average fiber diameter of 0·4 mm.

Figure 5 shows the load–deformation relationships of the nonwoven and the composite geotextiles. These results were obtained from uniaxial tensile tests, in which unconfined specimens with an aspect ratio of 8 were elongated at a strain rate of 2% per minute (Ling *et al.*, 1991, 1992). Whereas it is well recognized that the woven inclusion in the composite geotextile produces a higher stiffness and strength than that obtained in the

TABLE 2
Index Properties of Geotextiles

Geotextile	*Mass/unit area, m_f (g/m²)*	*Thickness t_{g0} (mm)*	*Apparent opening size, AOS (mm)*
Nonwoven	320	3	0·175
Retrieved	460	4	0·178
Composite	440 (woven = 120)	3 (woven = 0·5)	0·065

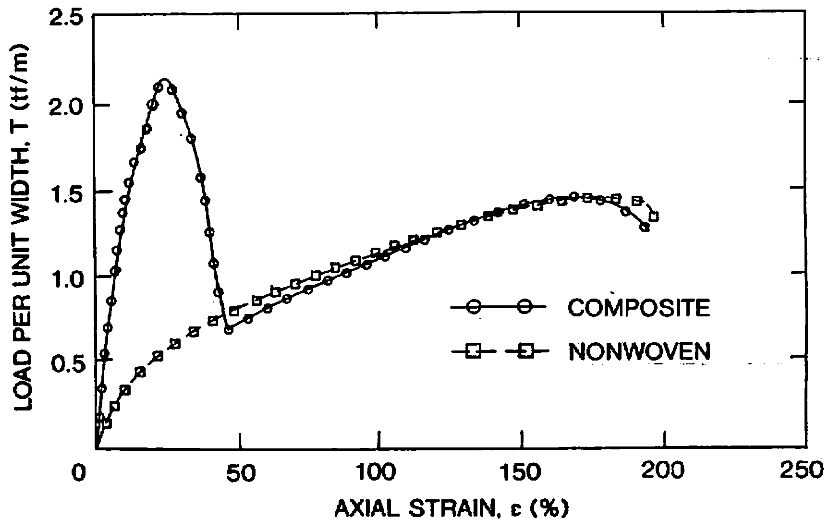

Fig. 5. Load–strain relationship of nonwoven and composite geotextiles.

nonwoven geotextile of the same density, little is known about the effect it has on the hydraulic conductivity.

The flow behavior in a geotextile subject to large tensile stresses was not investigated in this study. Field monitoring of full-scale structures has shown that the strains in the geotextile are relatively small, usually less than 2% (Tatsuoka *et al.*, 1991), as a result of the very high safety margin inherent in the current design method for these structures. The results of this study are believed to be justification for this under typical operational conditions.

4 TESTING PROGRAM

For the nonwoven and composite geotextiles, the cross-plane hydraulic conductivity under stress confinement and the in-plane hydraulic conductivity at different stress levels and with different confinement materials were measured. By using the same testing procedure, the in-plane hydraulic conductivity of the retrieved geotextiles was measured and compared with that of the virgin specimen. A new performance test was also included in this study.

4.1 Cross-Plane Flow Tests

The permeameter as suggested by ASTM D 4491 cannot be used for measuring the cross-plane hydraulic conductivity of a geotextile under stress confinement. On the other hand, the conventional permeameter used for measuring soil conductivity in which the specimen is confined by using two porous disks (e.g. ASTM D 2434) is not appropriate for this purpose because the porous disks are usually less permeable than the geotextile and may control the flow behavior. In this study, stresses were applied to the geotextiles through rigid meshes lined with densely spaced metal strips so that they did not control the flow while allowing the confining stress to be transferred uniformly to the geotextile. Three sheets of geotextile specimens in a stack were used in each test to obtain a representative value of the hydraulic conductivity. The use of too many sheets of specimens in a single test is not recommended because they may deform non-uniformly under a lateral confining pressure, and this may alter the flow behavior. Tests at zero effective stress were performed by clamping the piston rod while applying a small lateral confining pressure around the specimen's edges to prevent possible water leakage.

4.2 In-Plane Flow Tests

An in-plane flow test of a geotextile is usually performed by using the so-called parallel-flow device, of ASTM D 4716, in which the flow occurs parallel to and between two rigid plates. However, the effective flow area of a geotextile is believed to be significantly affected by the material used to confine it, and, in this series of tests, different methods of confinement — block-confinement, soil-confinement, and membrane-confinement — were used (Fig. 6(a), (b) and (c)).

The block-confinement tests were performed by sandwiching a geotextile specimen between two rigid rectangular acrylic blocks. To enable the applied stress to be distributed uniformly in the plane of the geotextile, one of the blocks was made a few millimeters shorter than the other to allow for free movement in the lateral direction. The other block had its two ends in direct contact with the cap and the pedestal and was set coaxial with the

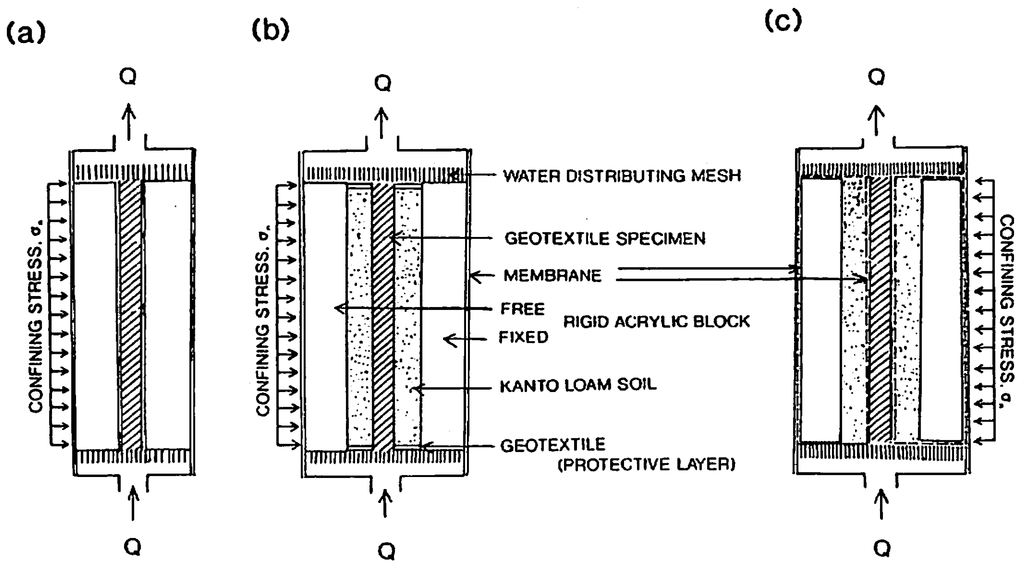

Fig. 6. Configuration of in-plane flow test: (a) block-confinement test; (b) soil-confinement test; (c) membrane-confinement test.

loading axis to prevent inadvertent rotation of the cap, which might hinder the movement of the shorter block.

The soil-confinement tests were performed by placing two compacted soil cakes on each side of the geotextile. Kanto loam was used for this purpose. By sufficiently compacting the soil and attaching geotextile to the bottom and top edges of the soil cakes as shown in Fig. 6(b), erosion of the soil was successfully prevented. It should be noted that the small thickness of clay, less than 1 cm, was used in order to minimize the effect of soil consolidation.

The membrane-confinement test was performed in the same manner as the soil-confinement test except that a piece of flexible latex-rubber membrane was introduced between the geotextiles and the soil cakes to prevent soil particles from penetrating into the geotextile matrix while providing a better confinement.

The geotextiles were tested mostly in their machine direction; tests in the cross-machine direction were performed only under the block-confinement condition.

4.3 In-Plane Flow Tests with Retrieved Geotextiles

For the cross-plane flow in a soil–geotextile system, the 'filter cake' formed in the soil adjacent to the geotextile surface controls the long-term flow behavior. On the other hand, for the in-plane flow, the retention of soil particles in a geotextile could be detrimental. To investigate the effect of soil penetration/retention on the hydraulic conductivity of a geotextile that has been embedded in soil for an extended period of time, three geotextile specimens retrieved from different locations in the test embankment previously described (Fig. 2) were measured. For the purpose of comparison, a virgin specimen of the same geotextile was also tested. The procedure for determining the in-plane hydraulic conductivity of these retrieved specimens followed closely that of the soil-confinement test. The field-retrieved specimens were soaked inside the test apparatus for about an hour before the tests were performed.

4.4 Performance Test

The long-term flow behavior in a soil–geotextile system is usually examined by the gradient-ratio test (Calhoun, 1972; Haliburton & Wood, 1982) or the long-term flow test involving the use of a soil column (Koerner & Ko, 1982; Lawson, 1982; Rollin & Lombard, 1989). The flow in these tests is one-dimensional and does not provide a realistic simulation of the stress and flow conditions in the field. Typically, the geotextile and the soil in the field are both subject to a confining stress, and the flow occurs two-dimensionally, with water infiltrating through the soil into the geotextile and being drained in its plane.

A new performance test was devised, as shown in Fig. 7, which allows a better simulation of flow condition in the field. Two blocks of soil, each with a flow area of 65 cm^2 and a minimum flow path of 5 cm, were compacted separately inside a mold at natural water content. A piece of nonwoven geotextile was then wrapped around the bottom block, over which the top block of soil was placed. The soil–geotextile composite was subjected to an effective confining stress of 0·3 kgf/cm^2 (29·4 kPa) and a

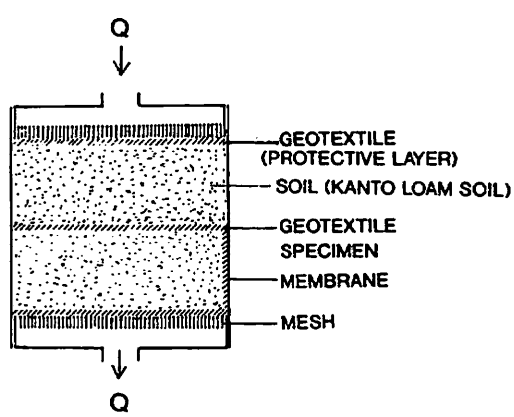

Fig. 7. Simulated model test of soil–geotextile system.

total hydraulic head loss of 100 cm. The test was continued until the flow had attained a state of equilibrium and showed no sign of further reduction in its flow rate.

4.5 Testing Procedure

In all the tests, precautions were taken to ensure that no air was trapped in the specimen and its interfaces and along the flow paths joining the specimens and the water supply/receiving tanks. After attaching the latex membrane to the pedestal and setting up the geotextile in place, water was introduced to displace the trapped air before sealing the membrane to the top cap. The pressure cell was then assembled and partly filled with water (see Fig. 3). A small air pressure was applied so that the excess water would flow into the tanks to provide an air-free flow path. The water from both tanks was then drained and the supply tank provided with new deaired water before starting the test. This method was found to be very effective in creating an air-free path without having to back pressurize the geotextile specimen (Ling *et al.*, 1992). Great care was taken not to pre-stress the geotextile during sample preparation.

When a geotextile is subject to flow, the head loss in its thickness direction is generally small. The cross-plane flow tests were therefore performed with a hydraulic gradient of up to 0·25 for the nonwoven geotextile and up to 1·45 for the composite geotextile. The effective normal stress was varied from 0 to 1·5 kgf/cm^2 (from 0 to 147·2 kPa) in the cross-plane tests and up to 1·2 kgf/cm^2 (117·7 kPa) for the in-plane tests. At each stress level, varying values of hydraulic gradient,up to a maximum of 3, were used. The tests were performed at 20°C in the laboratory.

5 HYDRAULIC PROPERTIES OF GEOTEXTILES

5.1 Geotextile Thickness at Different Stress Levels

The thickness of geotextile, t_g, which is a function of the stress level and stress history (see Fig. 8a), is required for determining the coefficient of hydraulic conductivity. In this study, the change in thickness of a geotextile at a given stress level was measured by a displacement transducer in the cross-plane flow tests. Although the change in thickness showed a time-dependent behavior due to creep, an averaged value during each test at the given stress level was used.

By measuring the strain of the geotextile, its thickness is calculated as

$$t_g = (1 - \varepsilon_n) t_{g0} \qquad (1)$$

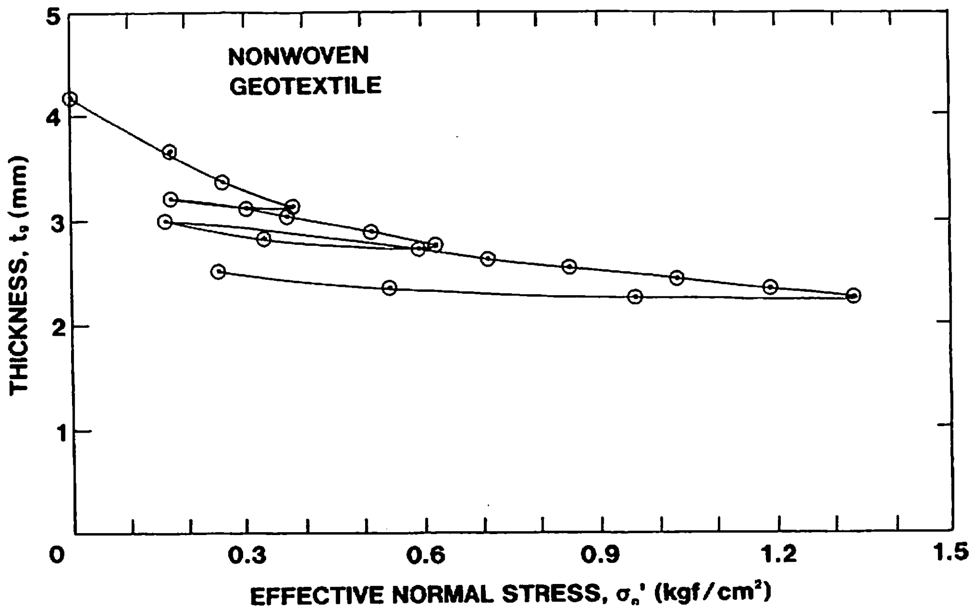

Fig. 8a. Variation of geotextile thickness with confining stress.

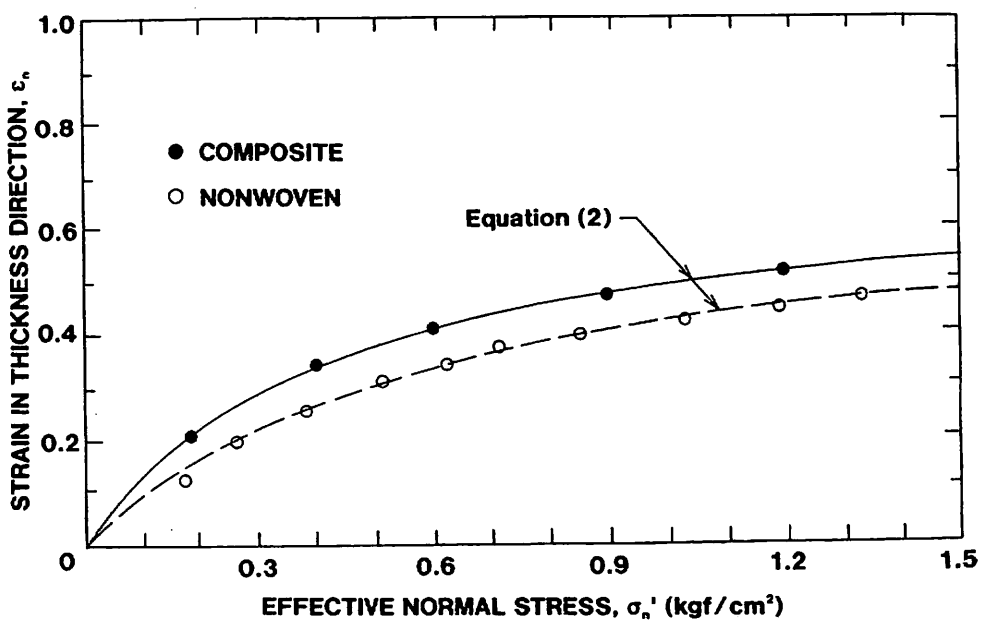

Fig. 8b. Fitting of experimental results by using hyperbolic equation.

where ε_n is the compressive strain in the thickness direction of geotextile, and t_{g0} is its initial thickness. The following hyperbolic equation has been found to be representative of the relationship between ε_n and the effective normal stress, σ_n', of the nonwoven and composite geotextiles at monotonic loading (Ling & Tatsuoka, 1991):

$$\varepsilon_n = \frac{\sigma'_n}{(E_{ci} + \frac{\sigma'_n}{\varepsilon_{ult}})} \tag{2}$$

where E_{ci} is the initial modulus of compression and ε_{ult} is the ultimate value of compressive strain. The parameters E_{ci} and ε_{ult} are equal to 0·9 kgf/cm^2 (88·2 kPa) and 0·67, respectively, for the nonwoven geotextile, and 0·6 kgf/cm^2 (58·8 kPa) and 0·71, respectively, for the composite geotextile. The equation fits the experimental data well, as is shown in Fig. 8b. Equation (2) was used to obtain the values of t_g of the specimens in the in-plane flow tests. The retrieved geotextiles, however, did not follow eqn (2) because they had been pre-stressed under the embankment load and soil particles had encroached into their voids. Their thicknesses were therefore obtained directly by a compression test.

5.2 Coefficient of Hydraulic Conductivity, Permittivity, and Transmissivity

The ease of flow through a porous medium can be expressed by the coefficient of hydraulic conductivity, which is commonly known as the coefficient of permeability. For the geotextile, the coefficients of hydraulic conductivity are usually normalized by its thickness, t_g, to give the permittivity, ψ, and transmissivity, θ, for the cross-plane and in-plane flows, respectively.

Consider a geotextile specimen with a width W, a length L, and a thickness t_g. The cross-plane hydraulic conductivity, k_n, and permittivity, ψ, are expressed as:

$$k_n = \frac{q}{WL}\frac{t_g}{h} \tag{3}$$

and

$$\psi = \frac{k_n}{t_g} = \frac{q}{WL}\frac{1}{h} \tag{4}$$

and the in-plane hydraulic conductivity, k_h, and transmissivity, θ, are expressed as:

$$k_h = \frac{q}{Wt_g}\frac{L}{h} \tag{5}$$

and

$$\theta = k_h \cdot t_g = \frac{q}{W}\frac{L}{h} \tag{6}$$

where q and h are, respectively, the flow rate and head loss in the flow direction. The above equations are usually corrected to a standard temperature by using a correction factor based on the absolute viscosity of water.

Although permittivity and transmissivity have been widely used in engineering design (Koerner, 1990), the results in this paper are presented in terms of the coefficient of hydraulic conductivity. This is because permittivity and transmissivity do not allow a direct comparison of the hydraulic conductivity of geotextiles with different thicknesses or evaluation of different testing methods.

6 EFFECT OF CONFINING STRESS ON HYDRAULIC CONDUCTIVITIES

Figure 9a shows the relationships between flow velocity and head loss for cross-plane flow in the nonwoven and composite geotextiles at the effective normal stresses of 0·2, 0·6, and 1·2 kgf/cm^2 (19·6, 58·9 and 117·7 kPa). The values of the head loss have been corrected for the apparatus compliance. It is evident that the flow behavior did not strictly obey Darcy's Law, since there existed a small threshold hydraulic gradient below which the flow was not detected. Since the average thicknesses of the composite and the nonwoven geotextiles were 0·42 cm and 0·27 cm, respectively, the threshold hydraulic gradient was about 0·05 for the composite geotextile and 0·04 for the nonwoven geotextile. However, for the in-plane-flow behavior shown in Figs 10a and 10b, the threshold hydraulic gradient was negligibly small when compared with the range of the hydraulic gradient examined. Transient or turbulent flow was not detected within the range of the hydraulic gradient investigated in this study.

Resulting from the threshold hydraulic gradient, the value of permittivity is a function of the flow velocity at low stress levels, as shown in Figure 9b, but this diminishes under a higher confining stress. Flow nonlinearity in soil at a low hydraulic gradient has been a debatable issue among researchers (for example Mitchell, 1976), and the reason for its existence has not yet been established. Olsen *et al.* (1985), however, considered it as a measurement error in the constant-head and the falling-head testing methods.

Figure 11a shows the relationship between a parameter b, which is the inverse of k_n, and the effective normal stress, σ'_n. It may be seen that the parameter b increases linearly with the effective normal stress as expressed by the following function:

$$b = b_0 + S\sigma'_n \tag{7}$$

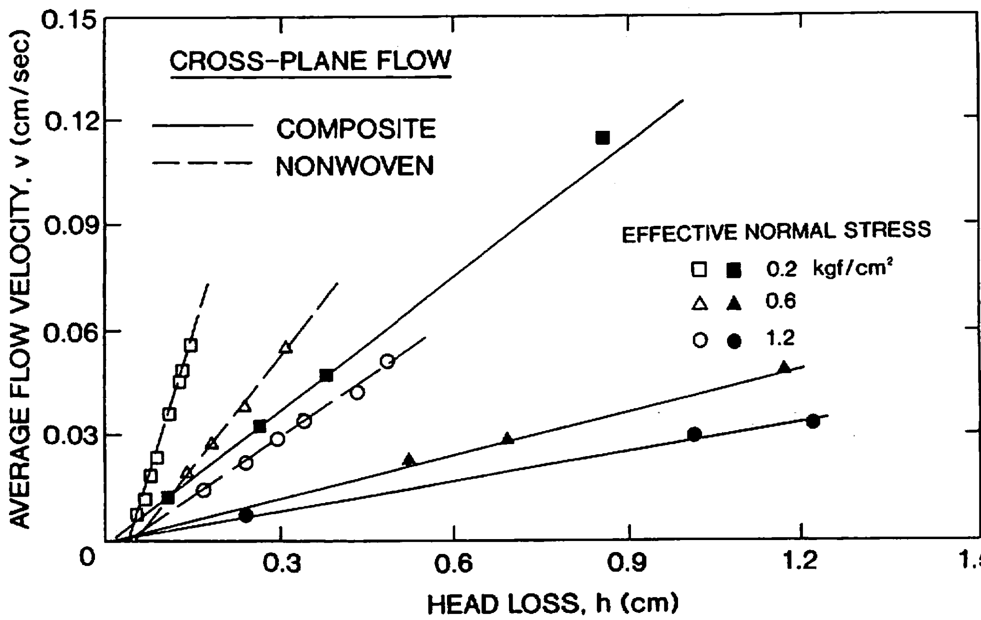

Fig. 9a. Relationship between flow velocity and head loss for cross-plane flow.

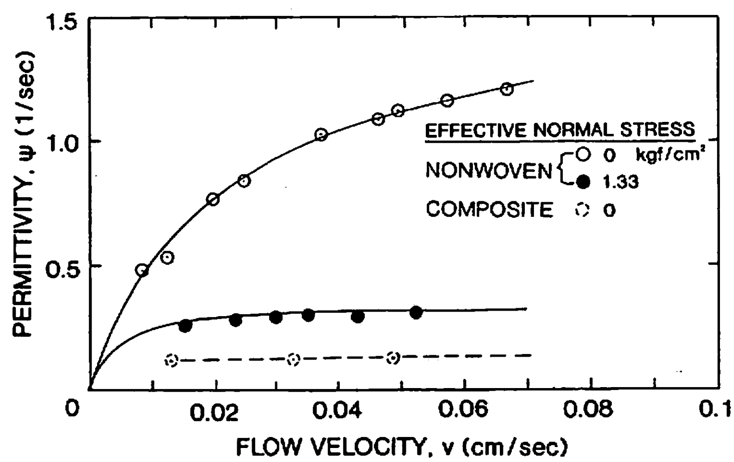

Fig. 9b. Relationships between permittivity and flow velocity.

where b_0 is the value of b at zero effective normal stress and S is the rate of increase of b (or the rate of decrease in hydraulic conductivity) with stress. The fitted curves shown in Figs 11a and 11b, which are based on eqn (7), seem to be valid. A higher-order polynomial can be used if a wider range of stress level is involved, and this linearity then no longer holds. This equation is also valid for representing the in-plane hydraulic conductivity of the geotextiles, as shown in Figs 12a and 12b for the nonwoven geotextile, and in Figs 13a and 13b for the composite geotextile. The

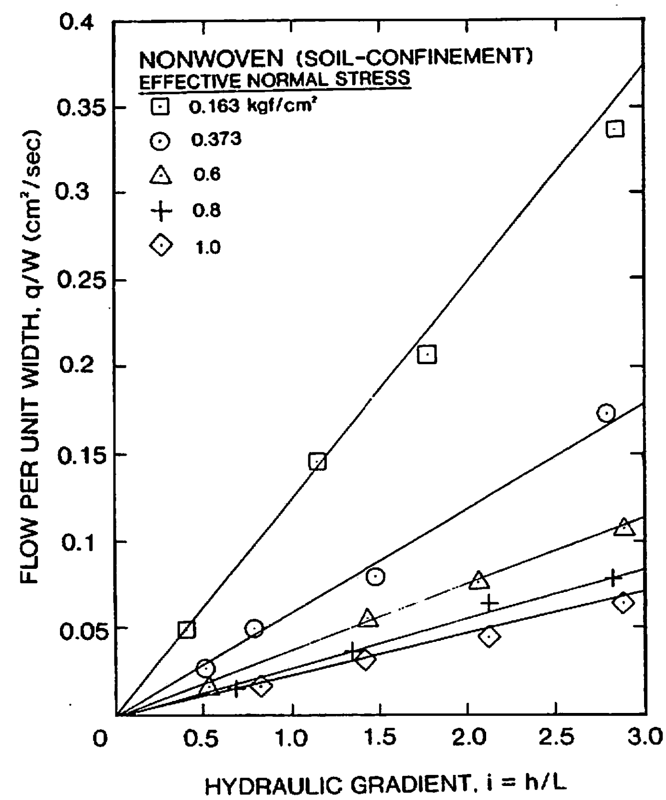

Fig. 10a. Validity of D'Arcy's Law for in-plane flow of the nonwoven geotextile.

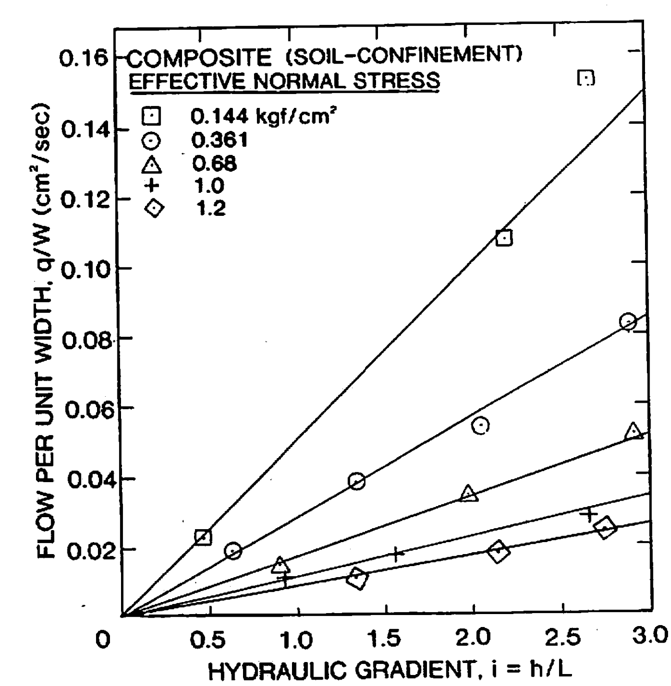

Fig. 10b. Validity of D'Arcy's Law for in-plane flow of the composite geotextile.

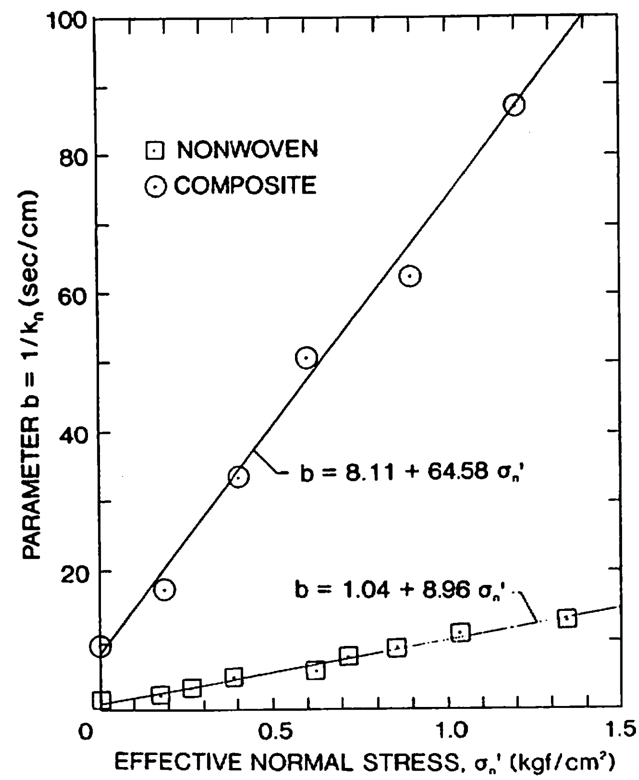

Fig. 11a. Relationship between parameter *b* and effective normal stress for cross-plane flow.

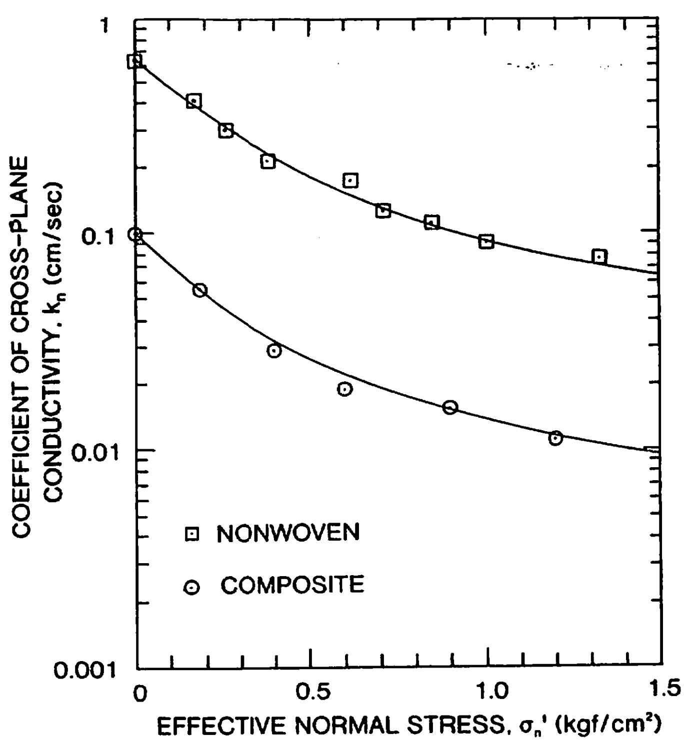

Fig. 11b. Relationship between cross-plane hydraulic conductivity and effective normal stress.

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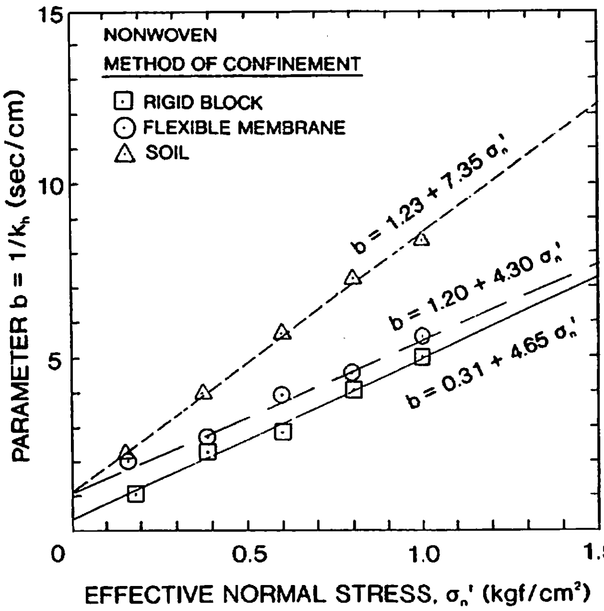

Fig. 12a. Relationship between parameter b and effective normal stress for in-plane flow of the nonwoven geotextile.

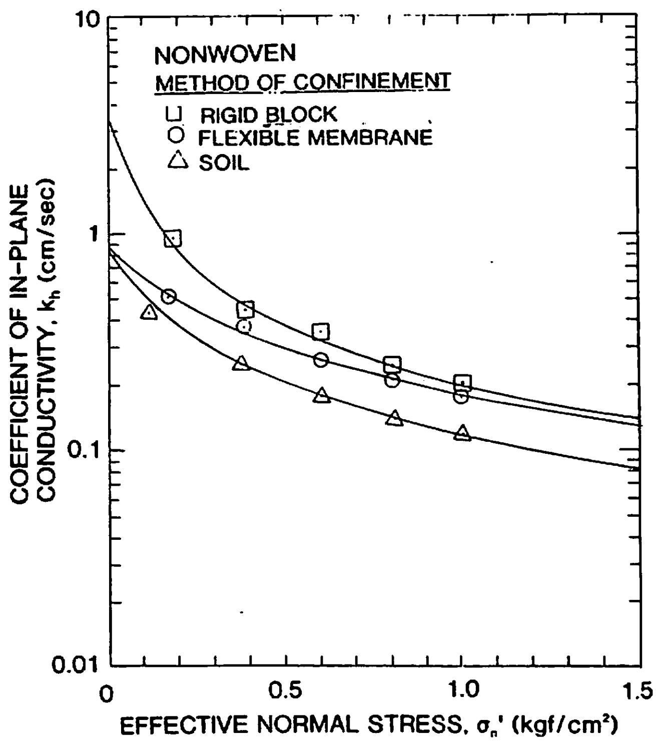

Fig. 12b. Relationship between coefficient of in-plane hydraulic conductivity and effective normal stress for the nonwoven geotextile.

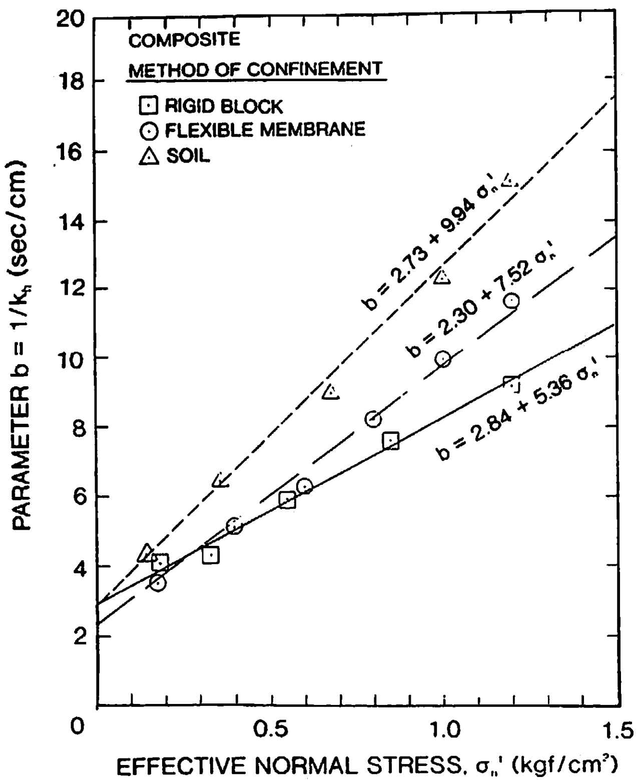

Fig. 13a. Relationship between parameter b and effective normal stress for in-plane flow of the composite geotextile.

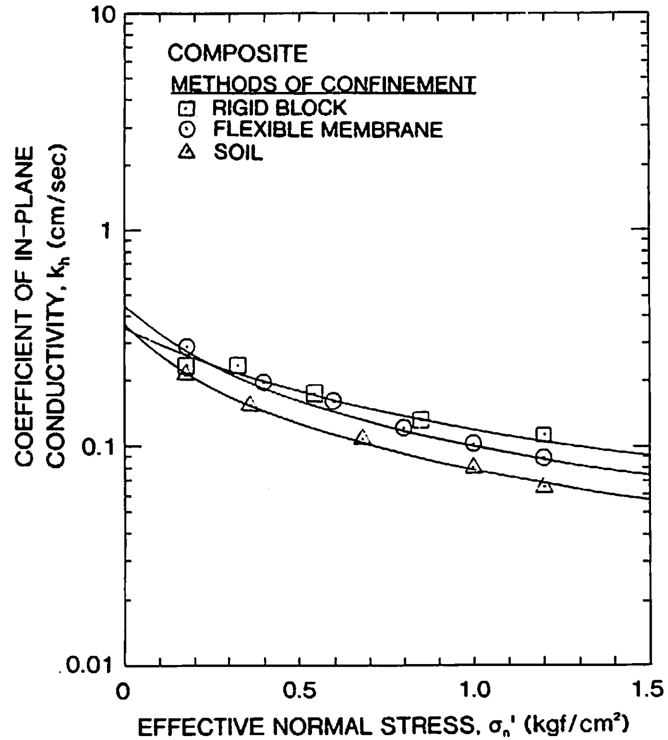

Fig. 13b. Relationship between coefficient of in-plane hydraulic conductivity and effective normal stress for the composite geotextile.

TABLE 3
Coefficients of Hydraulic Conductivity under Stress Confinement

Geotextile/Direction	b_0 *(s/cm)*	S *(cm.s/kgf)*	$k_0 = 1/b_0$ *(cm/s)*	$\beta = Sk_0$ *(cm²/kgf)*
Nonwoven, cross-plane	1·04	8·96	0·962	8·615
Composite, cross-plane	8·11	64·58	0·123	7·963
Nonwoven, in-plane				
Block	0·31	4·65	3·226	15·000
Membrane	1·20	4·30	0·833	3·583
Soil	1·23	7·35	0·813	5·976
Composite, in-plane				
Block	2·84	5·36	0·352	1·887
Membrane	2·30	7·52	0·435	3·270
Soil	2·73	9·94	0·366	3·641

equation has, in fact, been found to be valid for the retrieved geotextiles.

For convenience, eqn (7) can be rewritten as:

$$k = \frac{k_0}{1 + \beta\sigma'_n} \tag{8}$$

where $k_0 = 1/b_0$ is the coefficient of hydraulic conductivity in the unconfined condition, and $\beta = Sk_0$ is a coefficient indicating the rate of decrease of k with confining stress. Table 3 summarizes the values of b_0, S, k_0, and β for the nonwoven and composite geotextiles.

7 EFFECTS OF CONFINING MATERIAL ON IN-PLANE HYDRAULIC CONDUCTIVITY

Figures 12 and 13 show the hydraulic conductivity of the nonwoven and composite geotextiles under three different methods of confinement: those using rigid blocks (the block-confinement test), flexible membranes (the membrane-confinement test), and soil cakes (the soil-confinement test). It may be seen that the coefficient of in-plane hydraulic conductivity, k_h, was higher in the block-confinement tests than in the membrane- and soil-confinement tests for both geotextiles. The ratio of the coefficient of hydraulic conductivity determined by the block-confinement test to that of the soil-confinement test is approximately 2 at an effective stress of 1 kgf/cm² (98 kPa).

The difference in the hydraulic conductivities determined by these tests was apparently due to the different interface condition between the

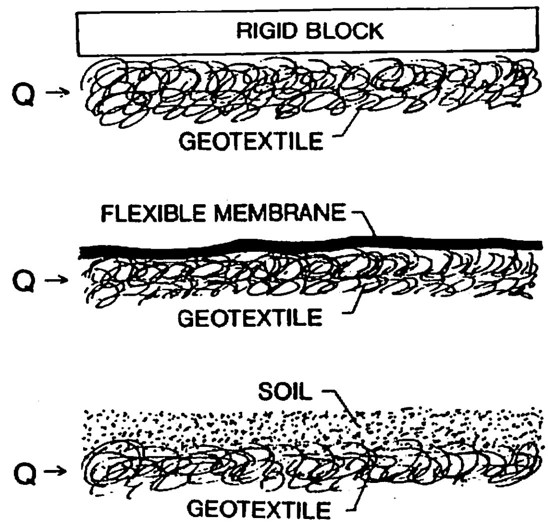

Fig. 14. Interface conditions of block-confinement, membrane-confinement, and soil-confinement tests.

geotextile and the confining materials, as schematically illustrated in Figure 14. As may have been expected, the flow rate was larger for a larger interface gap existing between the geotextile surface and the stiffer planar confining material when the rigid blocks were used, and a smaller flow rate resulted when a flexible membrane, which formed a closer contact with the geotextile, was used. Because of this mechanism, the difference in the coefficient of in-plane hydraulic conductivity between the membrane- and the soil-confinement tests increases with increasing effective normal stress.

In addition to the different interface condition, penetration of soil particles into the geotextile was also responsible for the difference in the hydraulic conductivity between the membrane-confinement and the soil-confinement tests. Soil particles were 'squeezed' into the geotextile upon application of the confining pressure. Some of the penetrated soil particles were subsequently transported away by the flow, whereas others were retained in the geotextile and thus reduced the void space. This can be observed in Figs 15(a) and 15(b), which show close-up views of a virgin geotextile specimen and an after-test geotextile specimen. The after-test specimen was an air-dried specimen obtained upon the completion of a soil-confinement test. It can be seen that the soil particles reduced the effective flow area by occupying part of the geotextile void formed between the fibers. From the test results, it is evident that the soil-confinement test is required for evaluating the in-plane hydraulic conductivity of a geotextile under operational conditions.

In this study, the void ratio, e, of a soiled geotextile was determined as:

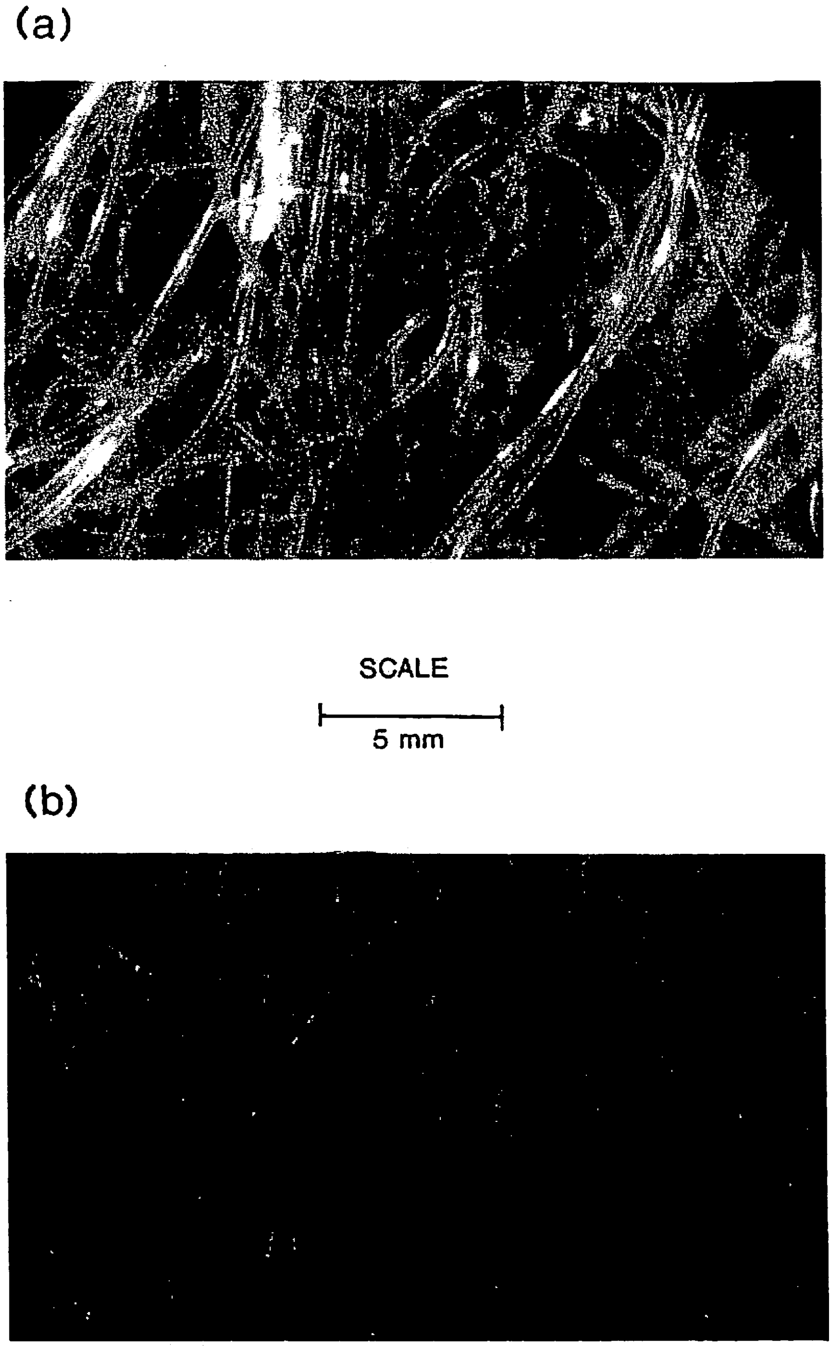

Fig. 15. Cross-section of geotextile: (a) fresh, (b) after soil-confinement test.

$$e = \frac{t_g}{\frac{m_f}{\rho_f} + \frac{m_s}{\rho_s}} - 1 \qquad (9)$$

where t_g is the thickness of the geotextile at the stress level considered, m_f and m_s are the masses per unit area of the geotextile and the soil, and ρ_f and

ρ_s are the densities of the fiber and the soil. The soil particles retained in the geotextile accounted for 15% increase in the dry mass per unit area. The void ratios of the nonwoven-geotextile specimens during the soil-confinement test, which were determined by using the values of m_f and m_s after the tests and during the block-confinement test, are shown in Fig. 16a. It indicates a significant reduction in the void space and hence in the hydraulic conductivity for the soil-confinement tests owing to the presence of soil particles.

Figure 16b shows the values of in-plane hydraulic conductivity plotted against the averaged void ratio of the nonwoven geotextile for the block- and soil-confinement tests. It may be seen that the reduction in hydraulic conductivity was due to the reduction in the total void space, the relationship of which can be expressed, for example, by the equations proposed for soil by Lambe and Whitman (1969) or by Juarez-Babillo (1983).

8 COMPARISON OF IN-PLANE HYDRAULIC CONDUCTIVITY BETWEEN VIRGIN AND RETRIEVED GEOTEXTILES

Figure 17 compares the in-plane hydraulic conductivity of the virgin and retrieved samples at different stress levels. The field-retrieved samples gave lower values of hydraulic conductivity than the virgin samples, and the difference is more pronounced at higher stress levels. There was a trend such that the closer the samples were located to the base of the embankment, the lower was the value of the hydraulic conductivity. For example, the sample located at the foundation of the embankment gave a value of in-plane hydraulic conductivity one-third that of the virgin sample, both values being determined by the soil-confinement test.

It has been shown in Section 7 that the reduction in hydraulic conductivity could be partly attributed to soil penetration and retention in the geotextile, which led to a reduction in the void ratio. The degree of retention (DOR), which is here defined as the ratio of the mass of soil retained in a geotextile to the mass of the geotextile free from soil retention, was used to investigate the reduction in conductivity due to soil retention. After each test, the geotextile specimen was rinsed thoroughly so that its mass free from soil retention could be obtained. The averaged DOR for the specimens retrieved from the test embankment was 43%, which was three times as high as that of the soil-confinement test with virgin specimens.

The DOR of the geotextile samples retrieved at various locations of the embankment, including those measured in this study, are plotted in Figure 18. There was a tendency for the samples located closer to the base

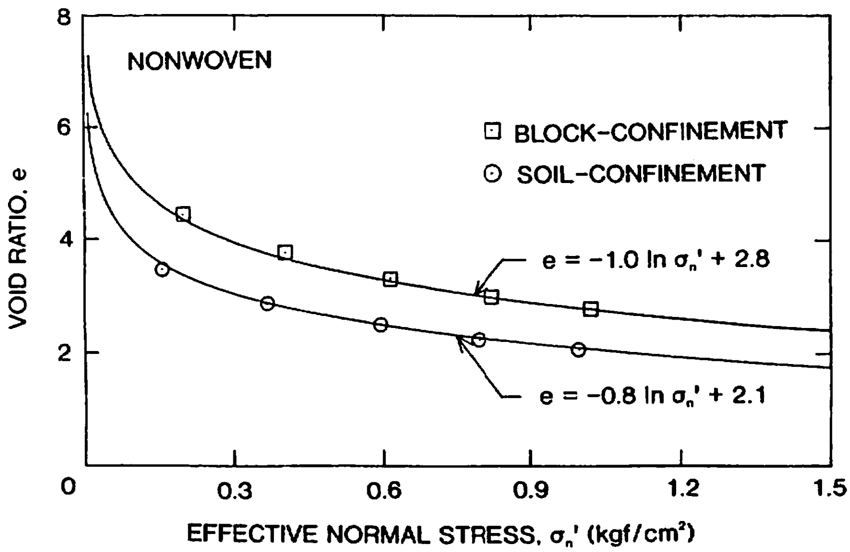

Fig. 16a. Relationship between void ratio and effective normal stress for the nonwoven geotextile under block and soil confinement.

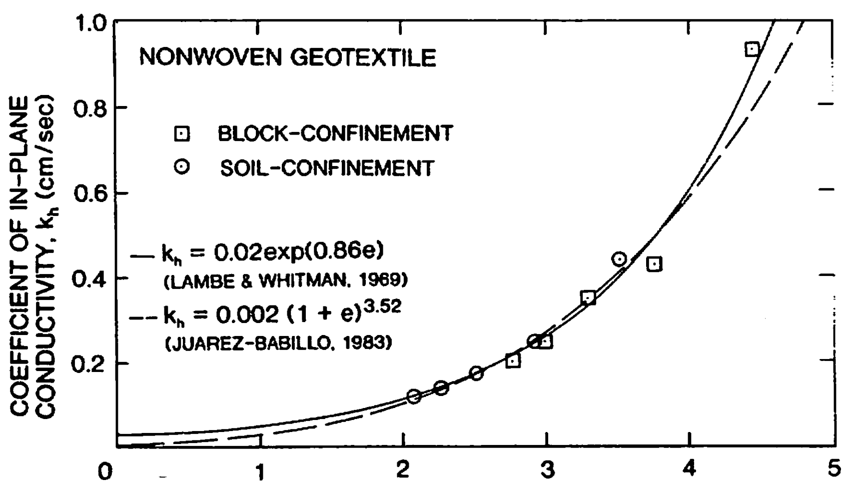

Fig. 16b. Relationship between coefficient of in-plane hydraulic conductivity and void ratio for the nonwoven geotextile.

and the crest to exhibit a larger value of DOR. The larger values of DOR are likely because the geotextiles at these locations had played a more active role in dissipating excess pore-water pressure during and after construction when compared with those located close to the crest.

The limited data obtained from this study suggested that a proportional relationship exists between reduction in in-plane hydraulic conductivity and DOR. For the geotextiles investigated in this study, one-third of the

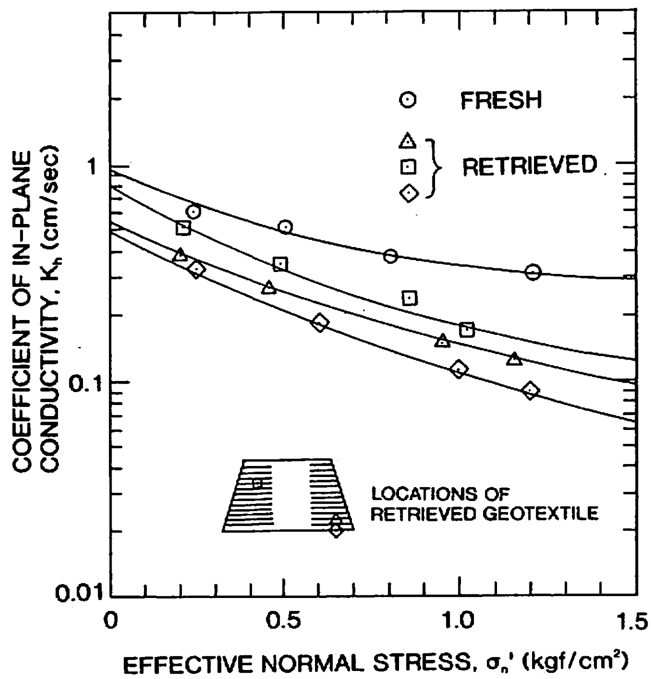

Fig. 17. In-plane hydraulic conductivity of retrieved-geotextile specimens.

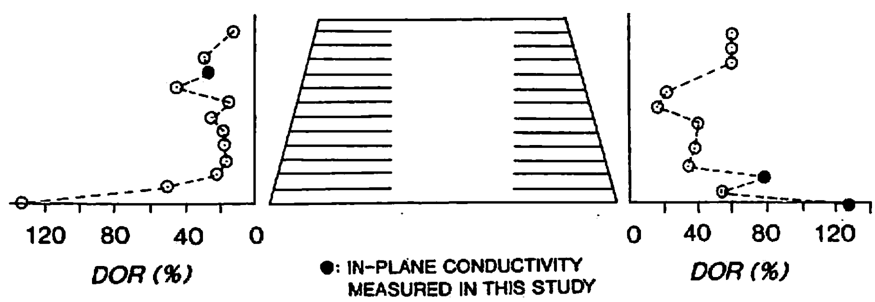

Fig. 18. Degree of soil retention of retrieved geotextiles.

value of in-plane hydraulic conductivity resulted from a threefold increase in DOR. More geotextile samples that have been subject to different stress and environmental conditions need to be tested for establishing a reliable general relationship between the reduction in hydraulic conductivity and DOR.

9 RESULTS OF TWO-DIMENSIONAL PERFORMANCE TEST

The results of the performance test as described earlier (Fig. 7) are shown in Figure 19 in the form of a relationship between flow rate and time. It may be seen that the flow rate decreases after the commencement of the

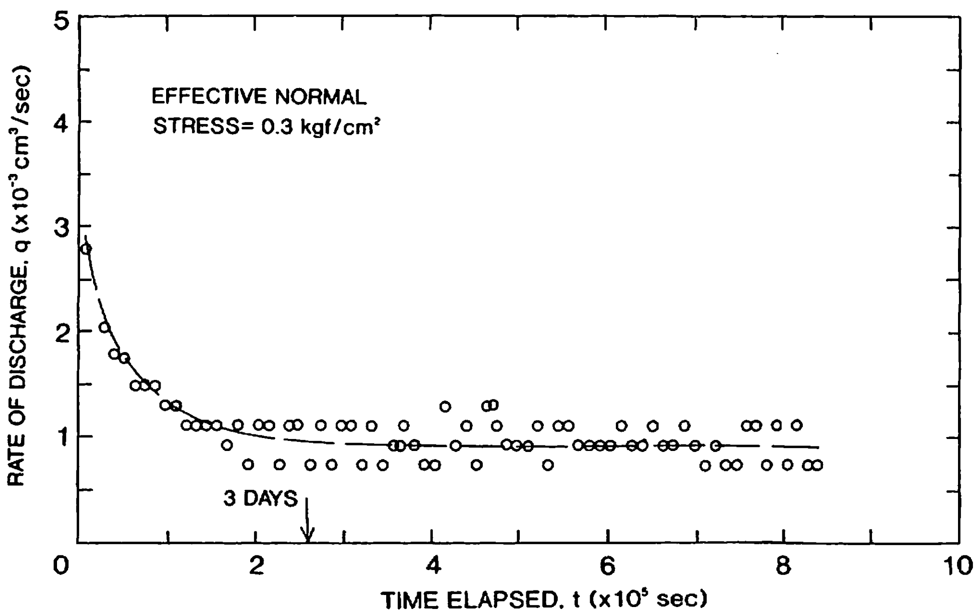

Fig. 19. Variation of flow rate with time in soil–geotextile model test.

test, and a steady state of flow was achieved after about three days. Beyond this equilibrium state, the flow remained very steady without any reduction in the flow rate for about twelve days until the test was terminated. The discharge was somewhat muddy during the first few minutes of the test and gradually became clear. The initial reduction of the flow rate before the steady state was reached could be partly due to the decrease in the void ratio of the soil resulting from consolidation.

It may be concluded from the test results that this geotextile serves its hydraulic function satisfactorily when embedded in Kanto Loam even under long-term conditions, as is evident from the satisfactory performance of the field-test embankment shown in Fig. 2. This may be explained by the clogging mechanism put forward by Rollin and Lombard (1988). Kanto Loam is a well-graded soil, and its particles were less mobile than those of a poorly graded soil in which a less permeable soil cake is more likely to form at the soil–geotextile interface owing to the movement of the smaller soil particles. The filter cake formed near the surface of a geotextile in Kanto Loam had probably nearly the same hydraulic conductivity as the base soil, and moreover, under stress confinement in this performance test, the soil particles became more tightly packed, and their mobility was further restrained. The flow was thus maintained in an equilibrium state.

It may be noted that the long-term flow test performed by Koerner and Ko (1982) showed that the equilibrium of flow was attained 200 hours after the test started, which was twice as long as this test, although the properties of the geotextile and the soil were comparable with those used in this study.

This may be partly because the soil in Koerner and Ko's test was left unconfined.

10 COMPARISON OF HYDRAULIC CONDUCTIVITY BETWEEN NONWOVEN AND COMPOSITE GEOTEXTILES

A comparison of the hydraulic conductivity of the geotextiles studied in the cross-plane and in-plane directions is given in Figure 20a. The nonwoven geotextile has a very similar coefficient of conductivity in its two directions under the stress levels examined, but the composite geotextile has a considerably lower value of cross-plane hydraulic conductivity than that in the plane. By using the measured values of k_n and t_g of the composite geotextile, and assuming that the cross-plane conductivity of the nonwoven part of the composite geotextile is similar to that of the nonwoven geotextile, the cross-plane conductivity of the woven inclusion was obtained by using the following expression and is plotted in Fig. 20a:

$$\frac{t_{g(c)}}{k_{(c)}} = \frac{t_{g(n)}}{k_{(n)}} + \frac{t_{g(w)}}{k_{(w)}} \tag{10}$$

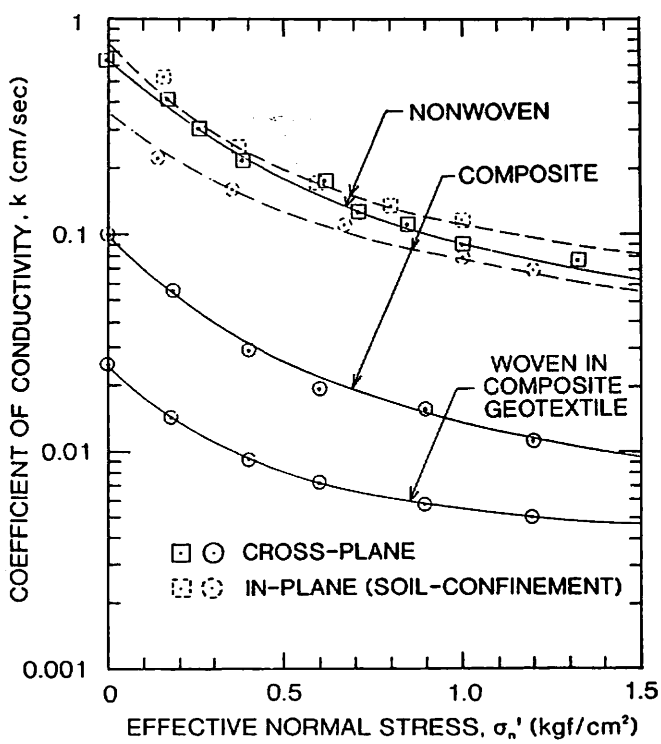

Fig. 20a. In-plane hydraulic conductivity of nonwoven and composite geotextiles.

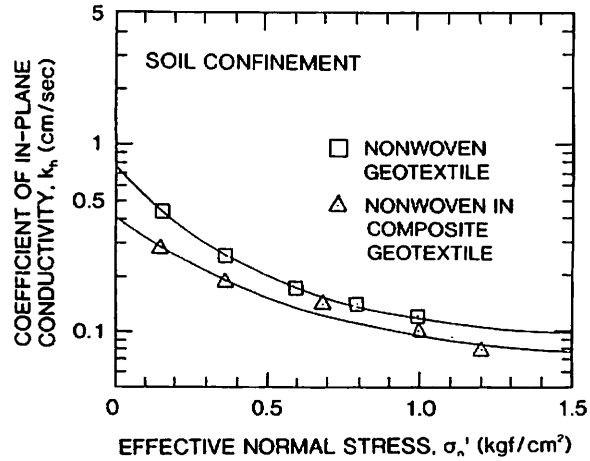

Fig. 20b. Effect of woven inclusion on the hydraulic conductivity of geotextiles.

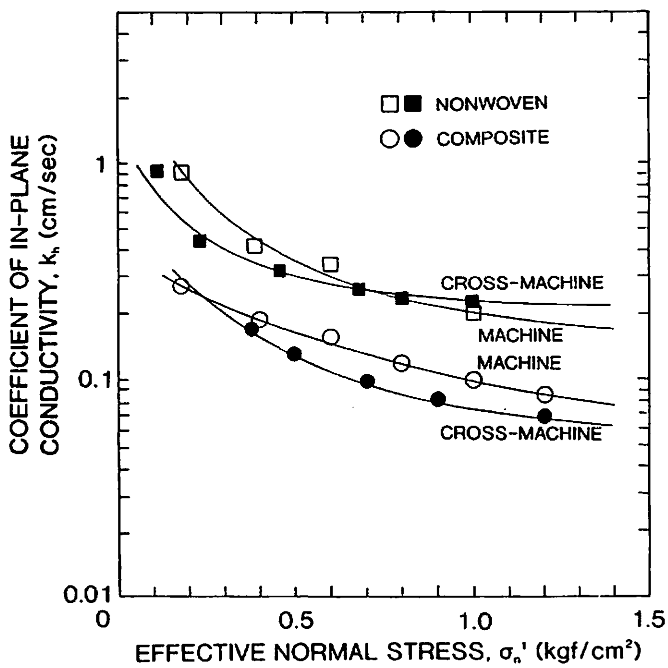

Fig. 20c. In-plane hydraulic conductivity in the machine and cross-machine directions of geotextiles.

where the subscripts (c), (w) and (n) denote the composite, the woven, and the nonwoven geotextiles, respectively. The low hydraulic conductivity of the woven inclusion, compared with that of the composite geotextile, indicates that the woven inclusion controls the cross-plane flow of the composite geotextile.

Comparing Figures 12a and 13a, it may be seen that the composite geotextile has a smaller in-plane hydraulic conductivity than the nonwoven geotextile. This is again due to the presence of the woven inclusion.

However, the effect of the woven inclusion on the in-plane flow is less significant when compared with that of the cross-plane flow because of the small ratio of the cross-sectional area of the woven to the composite in this flow direction. Assuming that the woven inclusion does not conduct any flow and its thickness can therefore be neglected, the value of in-plane conductivity for the nonwoven inclusion was obtained and plotted in Fig. 20b, which shows that the in-plane conductivities for the two geotextiles are rather close. This indicates that the woven inclusion in the composite conducts very little in-plane flow and has little effect on the in-plane conductivity of the nonwoven portions of the composite geotextile.

Figure 20c shows the coefficient of in-plane hydraulic conductivity of the nonwoven and the composite geotextiles in their machine and cross-machine directions. A slight degree of in-plane-flow anisotropy is observed for both geotextiles.

11 CONCLUSIONS

A study was undertaken to investigate the cross-plane and in-plane hydraulic conductivities of geotextiles under typical operational conditions. Laboratory tests were performed by using a newly developed testing device. Based on the results of this study, the following conclusions are drawn.

(i) A flow equation is proposed for simulating the cross-plane and in-plane flow behavior of geotextiles to include the effect of stress confinement. The parameter b in the flow equation, which is the reciprocal of Darcy's coefficient of hydraulic conductivity, is directly related to the effective normal stress by a linear function.

(ii) The in-plane hydraulic conductivities measured by using a rigid block, a flexible membrane, and soil as the confinement were rather different. The rigid-block-confinement test gave the highest hydraulic conductivity whereas that of the soil-confinement test was the lowest. The difference between the block- and membrane-confinement tests was due to the interface condition, whereas the difference between the membrane- and soil-confinement tests was primarily due to soil penetration/retention. An over estimation of in-plane hydraulic conductivity for a geotextile embedded in soil could result if the test were performed by using a rigid block or flexible membrane as the confinement.

(iii) The soil particles penetrating and retained in the geotextile matrix are a dominant factor affecting the long-term in-plane-flow behavior of geotextiles. The degree of retention, DOR, is an indicative index for correlating the soil type and field-installed geotextile. A higher DOR, about twice as high, was measured in the field-retrieved samples than in the virgin geotextile sample tested by using the same type of soil as the confinement, whereas the in-plane hydraulic conductivity of the retrieved geotextile samples was about one-third of that of the virgin geotextile samples.

(iv) The performance test with stress confinement proposed in this study is a more realistic test for simulating flow behavior under operational condition than the gradient-ratio test or the long-term cross-plane flow test in which the soil and geotextile are left unconfined. It is suggested that, under stress confinement, the soil particles become more tightly packed and less mobile relative to one another and therefore yield a more favorable flow behavior in a soil-geotextile system.

(v) In terms of the in-plane hydraulic conductivity, the composite geotextile performed equally well as the nonwoven geotextile of a similar density. The woven inclusion in the composite geotextile, however, controls its cross-plane hydraulic conductivity.

From the measured hydraulic conductivities of the geotextiles, it is known that they are several orders of magnitude greater than those of on-site cohesive soils including Kanto Loam. The geotextiles are regarded as effective for dissipating excess pore-water pressure during construction and draining infiltrated water in reinforced-soil structures with a cohesive backfill. Nevertheless, a sound design procedure that takes into consideration the hydraulic conductivity of the geotextile reinforcement has yet to be developed.

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