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Performance Tests of Geotextile Permeability for Tunnel Drainage Systems

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Abstract

In double-lined tunnels, geotextiles are installed between shotcrete and concrete linings to drain ground water that is in the circumferential boundary of the tunnels. During the concrete lining placement, the geotextile often experiences pressures from young concrete on the curved and rough shotcrete surfaces. The pressures are transferred through a waterproof membrane, and act in the normal direction to the curved shotcrete face. The geotextile flow behavior under these conditions cannot be represented by standard geotextile permeability tests. Instead, it requires specially designed performance tests that consider field conditions. A new device to evaluate the permeability of the geotextile in pressurized curved flow channels is proposed; it adopts a flexible loading system and a curved and rough model plate. Testing of geotextiles used for tunnel drainage systems, using the proposed arrangement, shows that the effects of the tortuousity of the flow in pressurized channels affects significantly the geotextile permeability.

Keywords: *geotextile, permeability, performance test, tunnel, drainage system*

1. Introduction

Permeability is one of the most difficult geotechnical parameters to evaluate because of its wide distribution range. An inaccurate evaluation of permeability may result in unnecessary over-sized hydraulic structures or in a lack of hydraulic capacity. Excessive hydraulic structure capacity increases construction costs; meanwhile, insufficiency of the hydraulic capacity may cause operational problems to the engineering structure.

As one of the main components of geosystems, geotextiles are used to control or guide groundwater flow while preventing soil particles from being scoured. Therefore, the permeability of geotextiles is also an important factor in designing structures with drainage systems. The flow rate through a geotextile is mainly governed by field conditions. The most important factor determining the permeability of a geotextile is the compressive stress, which applies pressure normal to the flow paths (Palmeira and Gardoni, 2002). For instance, in a double-lined tunnel, the geotextile for drainage is generally installed between the shotcrete lining and a water proofing membrane, as shown in Fig. 1. The surface of the shotcrete is undulated and considerably rough. During the placement of the concrete lining, young concrete exerts pressures on the geotextile surface. For a 10-m-high tunnel, young concrete pressures may reach up to 230 kPa. Additionally, seepage force causes sedimentation of fine particles in the drainage layer, which also reduces the permeability of the geotextile. Shin *et al.* (2002, 2005) and Shin (2008) investigated the effects of hydraulic deterioration of the tunnel drainage system and revealed that the reduction in geotextile permeability increases pore water pressure in the concrete lining and decreases the flow rate into the tunnel. Therefore, the evaluation of geotextile permeability is crucial in designing tunnel drainage systems, such as collecting wells, hydraulic pumps, and pumping stations.

The ASTM D4716–08 (2013) provides a standard method to determine the permeability of the geotextile. The standard testing system uses a steel loading plate for planar flow on a horizontal surface. This system cannot consider the above mentioned field conditions appropriately. ASMT D4716–08 (2013) recommends that performance testing should include a model of the nature of the material in contact with the geosynthetics in the field.

This paper describes and proposes a new in-plane permeability performance testing for evaluating the geotextiles in curved and rough flow paths such as in a tunnel drainage system. The effect of flow surface roughness is investigated by performing a tentative application of the new equipment.

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2. New Performance Testing Method

For the case of geotextiles in tunnel drainage systems, the in-plane flow is the main consideration. The standard in-plane permeability of the geotextile is evaluated by measuring the flow rate through the geotextile, which is in between steel plates. In ASTM D4716–08 (2013), the permeability (k_p) is determined based on Darcy's law as follows:

$$k_p = \frac{Q}{T_g \cdot i \cdot w} \quad (1)$$

where Q is the flow rate, T_g and w are the thickness and width of the specimen, respectively, and i is the hydraulic gradient. Eq. (1) is defined for flows in smooth flow paths. In the field, however, flow paths are not flat and smooth. In particular, the shotcrete surface in a tunnel drainage system is considerably rough. Louis (1976) and Hoek and Bray (1996) investigated the effect of roughness on permeability. By performing hydraulic experiments on rock joint flows, they expressed the permeability of joints as shown in Eq. (2).

$$k_i = \frac{ge^3}{12\,\nu bc} \quad (2)$$

where, $c = 1 + 8.8\left(\frac{n}{D_h}\right)^{1.5}$, g is the gravitational acceleration, ν is the dynamic viscosity of water, e is the joint aperture, b is the distance between joints, n is the roughness, and D_h is the hydraulic diameter (in this case $D_h = 2e$). Eq. (2) indicates that the joint permeability is strongly dependent on the roughness.

In the standard flat model plate testing method, the pressure is normal to the geotextile on a flat model plate. In curved flow paths the pressure on the geotextile is normal to the flow boundaries. However, the directionality of the stresses varies throughout the flow. The flow rate in a curved and rough flow channel would be much lower than that in a flat flow channel. The geotextile in this environment will have a higher flow resistance, resulting in a lower flow rate and a lower permeability. Thus, tests adopting a flat model plate may overestimate the actual permeability of the geotextile in a tunnel drainage system.

2.1 Basic Concept

With respect to performance testing for geotextiles in a tunnel drainage system, the ASTM D4716–08 (2013) cannot reproduce field conditions appropriately in the laboratory. For performance tests of geotextile permeability, a new device is considered to more accurately represent field stress distributions on geotextiles in curved and rough flow channels.

The field stress conditions are represented by introducing a flexible membrane loading plate pressurized by liquid. If the membrane stiffness is negligibly low, the plate deforms and closely fits the curved flow surface. Therefore, the field flow surfaces are better reproduced by using a curved and rough model plate similar to the actual flow boundaries.

If the geotextile is placed on the curved and rough plate, the

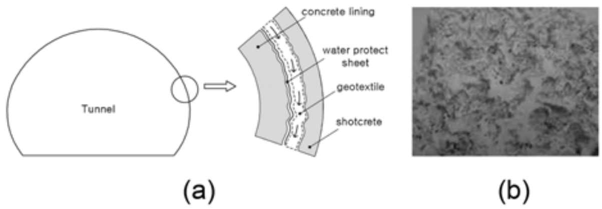

Fig. 1. Geotextile in Tunnel Drainage Systems: (a) Tunnel Drainage System, (b) Shotcrete Surface

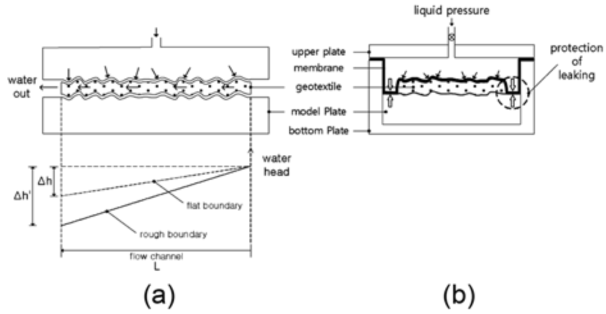

Fig. 2. Representation of Flow Characteristics: (a) Head Loss in Flow Channel, (b) Membrane Loading System (Lateral Section)

flow resistance increases; consequently, the water head difference increases from Δh to $\Delta h'$, as shown in Fig. 2(a). Thus, the hydraulic gradient increases and flow rate decreases. Consequently, a lower permeability is obtained.

2.2 Membrane Loading System and Rough Model Plate

Field stress conditions on the geotextile can be reproduced by using a flexible membrane loading system as shown in Fig. 2(b). When the pressure from air or from liquid such as oil is increased in the loading system, the flexible membrane deforms and fits to the curved boundaries, inducing normal stresses on the curved flow surface. In the device proposed in this study, latex rubber is used for the plate.

Generally, boundaries between sample edges and containing plates are apt to leak. In the proposed device, this problem can be easily and automatically resolved by pressurizing the contact between the loading membrane and the edges of the sample container, as shown in Fig. 2(b).

Generally, the surface conditions can be quantified by roughness. Once the representative roughness for a specific problem is identified, it can be reprinted on the model plate using a computer-aided laser cutter. It is alternatively recommended to prepare standard roughness plates based on the existing roughness categories prior to testing. One method to determine the standards is employing Barton's roughness chart (Barton and Choubey, 1977). Based on the chart, standard rough model plates with a series of roughness profiles can be made prior to the testing program. By investigating the field roughness conditions a best-fit model plate can be chosen from the pre-made plates. This approach provides engineering convenience and allows for the plates to be reused. Fig. 3(a) presents the procedure of the

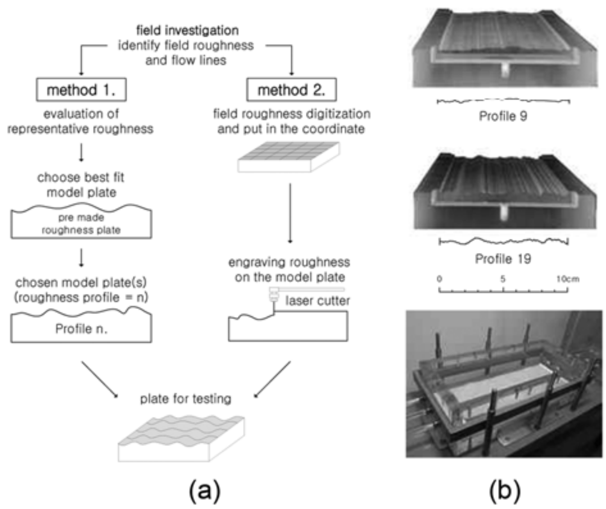

Fig. 3. Preparation of Model Plates: (a) Methods of Model Preparation, (b) Model Plate based on Barton's Profile

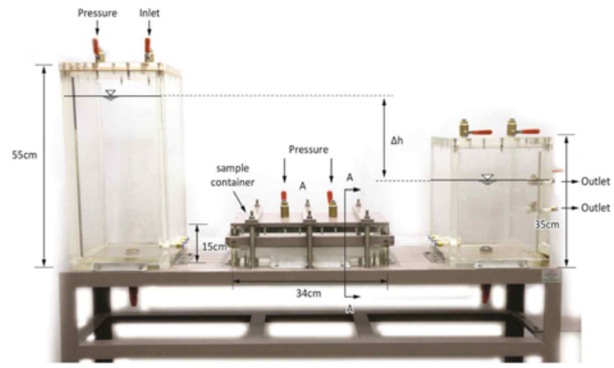

Fig. 4. Full Test Set Up

model plate preparation.

The test procedure using the new device is essentially the same as ASTM D4716–08 (2013), except for the preparation of the model plate and the membrane loading system. Once the model plate is assembled, a required pressuring of the system ensures that no leaks exist along the boundaries between the membrane and the sample container.

3. Applications: Example Tests

Permeability tests for the geotextile on the rough surface using the flexible loading plate were performed using the proposed testing device. Fig. 4 portrays the full test set up equipped with the rough model plates and the membrane loading system.

In order to investigate the effects of roughness, model plates

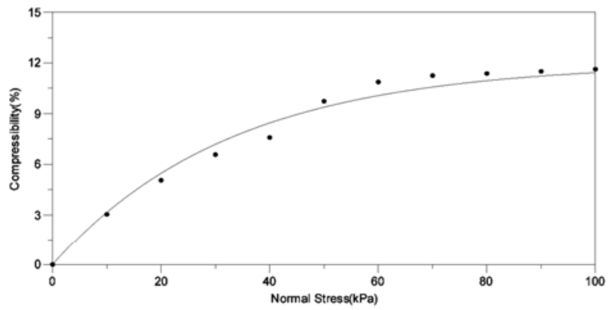

Fig. 5. Normal Stress and Compressibility

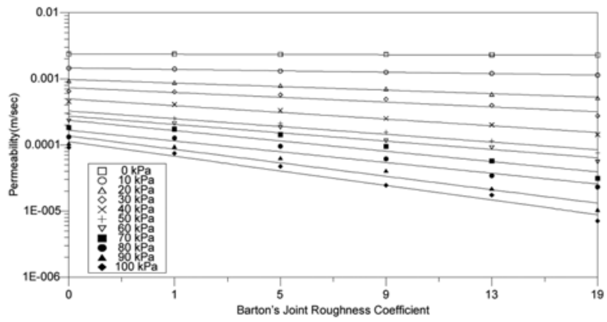

Fig. 6. Influence of the Roughness Coefficient on the Coefficient of Permeability for Different Normal Stresses

based on Barton's joint roughness coefficient profiles were prepared. Although the flow resistance is higher for the flow that is parallel to the profile, in these tests, only the flow that is normal to the profile is simply considered to investigate the effects of roughness. Acrylic model plates were prepared using the laser cutting method with the following Barton's profiles: 0, 1, 5, 9, 13, and 19.

The geotextiles used for the tests were needle-punched nonwoven long fiber polyesters. Table 1 shows the properties of the geotextile used. The compressibility of the geotextile due to normal stress is evaluated for the flat model plate, as it is not possible to determine the thickness of geotextiles on a rough surface under hydrostatic pressure. The compressibility (C) of the geotextile for varying normal stresses (σ) is represented as $C(\%) = 12(1 - e^{-0.03\sigma})$ and is shown in Fig. 5.

The permeability is calculated using the equation.

$$k_p' = \frac{Q'}{i' \cdot A} \tag{3}$$

where, A is the average cross section ($A = T_g' \cdot w$, $T_g' = (T_g - C \cdot T_g)$, where C is the compressibility of the geotextile), i' is the measured hydraulic gradient ($i' = \Delta h'/L$) and Q' is the measured flow rate. Fig. 6 shows the geotextile permeability for

Table 1. Properties of the Geotextile

Polymer	Manufacture method	Weight (g/m²)	Tensile Strength (t/m)	Elongation (%)	Seam Strength (kg)	Thickness (mm)	
						without loading	under 2kPa
Polyester	Needle Punching	450	5.51 (140 kg/in)	60~100	140	2.6	1.7

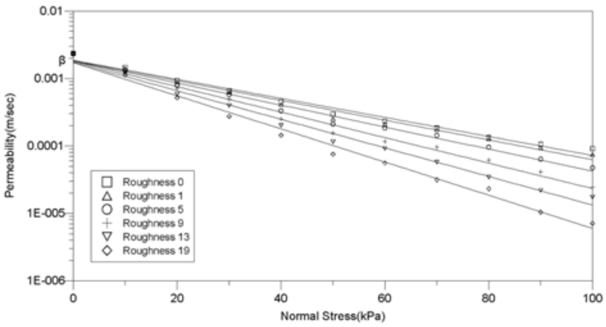

Fig. 7. Influence of the Normal Stress on the Permeability for Varying Roughness

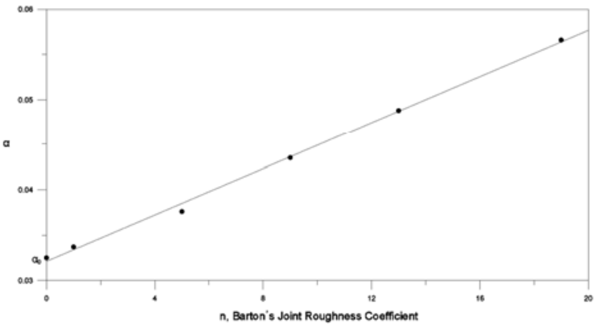

Fig. 8. Roughness Profile for α

varying roughness and normal stress. The permeability reduces significantly with an increase in roughness. This effect is more pronounced for higher normal stresses.

Figure 7 illustrates the effect of the normal stress on the geotextile permeability for different roughness. Geotextile permeability reduces exponentially with an increase in normal stress as shown in Eq. (4).

$$\ln k_p = -\alpha\sigma_n + \beta \quad (4)$$

where β is a constant and α is a factor depending on roughness. In these tests, the relationship between α and the roughness is linear, as shown in Fig. 8 and in Eq. (5).

$$\alpha = an + \alpha_0 \quad (5)$$

where, $a = 0.0012$ and $a_0 = 0.03$. The results presented were obtained for parallel flow to Barton's profile. However, actual roughness often varies three dimensionally. This feature needs to be considered in preparing the model plates.

4. Conclusions

An evaluation of geotextile permeability is crucial for designing drainage systems in tunnels. In many cases, geotextiles are installed between curved and rough boundaries, which cannot be represented appropriately by using the standard testing method. This requires a custom performance testing method that represents the actual field conditions.

In this paper, a new performance testing method for geotextile permeability is proposed. The test procedure proposed is essentially the same as the standard ASTM D4716–08 (2013). In the proposed method the use of the model plate and the membrane loading system allows to represent flow in curved and rough boundaries. The main advantages of the proposed method for geotextile permeability in comparison with the standard testing method are:

- It can consider roughness of the flow channel, therefore it represents more realistic conditions of the operation of the geotextile.
- The field roughness is categorized based on Barton's roughness coefficient and it can be reproduced for testing with a previously made plate.

The testing method has shown to represent field conditions appropriately and provide accurate permeability information on geotextiles. Example tests reveal that the curvature and roughness of flow channels significantly reduce the permeability of geotextiles, particularly for cases where the normal stress is high.

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