Hydraulic deterioration of geotextile filters in tunnel drainage system

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ABSTRACT: The discharge capacity of a tunnel drainage system generally decreases with time because of the hydraulic deterioration of the geosynthetic filter. The hydraulic deterioration of the geosynthetic drain material causes an increase in the water pressure, leading to structural damages to the tunnel lining. In this study, the deterioration mechanism of the tunnel drainage system was investigated. The stress increase in the lining and filter clogging were considered as the main factors resulting in the reduction of the permeability. The hydraulic deterioration was theoretically modeled considering the squeezing and clogging. An experimental study was conducted to identify the clogging behavior due to the sedimentation of soil particles, cement-leaching calcium oxide, calcium carbonate, and iron oxide, and validate the theoretical model. The predictions using proposed permeability model was generally consistent with the experimental results.

Keywords: Tunnel drainage system, Geosynthetic filter, Hydraulic deterioration, Water pressure

1 INTRODUCTION

The hydraulic deterioration of a drain system is largely due to the squeezing and clogging of the drain filters. Squeezing occurs when the load increases, resulting in decreased permeability due to the reduction in pores of the geotextile. The increase of stress can occur when the concrete lining is being placed during construction. Subsequently, the lining stress can also increase due to the increase in the external load around the tunnel during operation. Clogging generally occurs when particles move with the groundwater flow and block the pores of the geotextile drain filters or deposit on the filter surface. Figure 1 shows the tunnel drainage system.

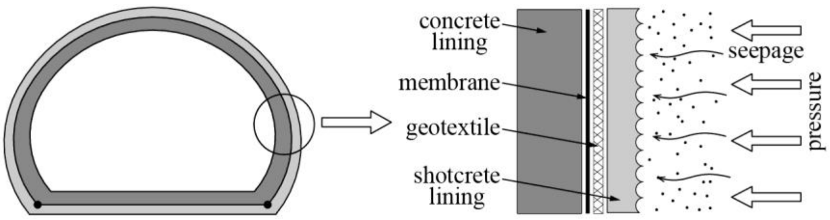


Figure 1. Tunnel drainage system

Many studies have been conducted on the hydraulic deterioration of geotextiles, wherein the pore clogging behavior of soil particles was analyzed using various methods (Fleming and Rowe 2004, Maheshwari and Gunjagi 2008). Hydraulic deterioration due to clogging has been reported to occur when particles deposit in the pores or on the surface of the geotextile drain filter. The particle size and the amount deposited on the geotextile determine the degree of hydraulic deterioration (Palmeira and Gardoni, 2002). Giroud (2005) proposed a permeability degradation model for the clogging of uniform soil particles by establishing a relationship between the soil particle characteristics and the pores in the geotextile.

The general hydraulic deterioration behavior of geotextiles has considerable engineering significance for tunnel drainage systems. However, it differs from the general geotextile drain filter in that the flow direction is not normal to the drain material but is rather in an in-plane direction. Moreover, the sediment not only comprises soil particles but also various other materials in the tunnel drainage system. The tunnel drain filter is installed between the shotcrete lining and concrete lining and is not in contact with the ground. Thus the geotextile filter is relatively unaffected by soil particles or organic matter. Instead, it is susceptible to grout or shotcrete leaching materials. Therefore, the hydraulic degradation model proposed by Giroud (2005) cannot be directly applied to evaluate the degree of hydraulic deterioration of the tunnel drain filter. Decrease in the in-plane permeability was greater than that in the normal permeability for the vertical loading (Palmeira and Gardoni 2002). The maximum mass of the captured particle in geotextile filter is generally constant regardless of the concentration of the clogging material (Faure et al. 2006).

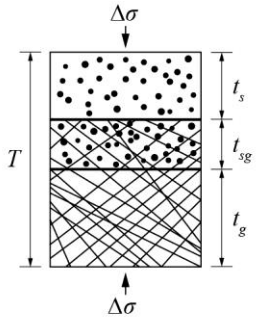
In this study, the factors affecting the hydraulic deterioration were selected by considering the tunnel construction environment, and the permeability degradation model of the tunnel drain filters was proposed. Clogging and permeability test were performed to investigate the clogging behavior and validate the proposed mathematical model. Several studies (Tan et al. 2018, Shin et al. 2014) have pointed out that the hydraulic deterioration of the drain filter can cause a structural burden, particularly with the increase in the hydraulic pressure of the tunnel lining.

2 THEORETICAL MODELING OF HYDRAULIC DETERIORATION

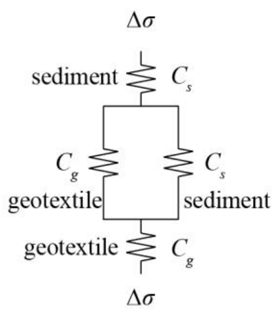
The existing hydraulic deterioration permeability model for geotextiles was derived on the basis of the micro-hydraulic behavior. However, the characteristics of compression and clogging mechanisms in the tunnel drainage system differ from those in the embankment filter drain. Therefore, it is inappropriate to predict the hydraulic deterioration behavior of the tunnel drainage system using existing model. The squeezing and clogging behaviors causing the hydraulic deterioration of the tunnel drainage system can be studied from the perspective of geotechnical hydraulic-displacement coupled behavior.

Conventional permeability degradation models take into account only the properties of the geotextile and soil particles, whereas the squeezing and clogging behavior is considered independently. However, the actual degradation occurs by interacting results between the load and clogging, and depends on various conditions affecting the particle infiltration and sedimentation.

Clogging starts to occur after the installation of virgin geotextile. Some particles infiltrate the pores and others deposit on the surface. Figure 2(a) shows the geotextile elements under loading conditions for various sedimentation conditions. The total thickness of the geosynthetic element including the sedimentation on the top is T; the thickness of the virgin geotextile is t_g; the thickness of the clogged geotextile is t_{sg}; and the thickness of the cake is t_s. Figure 2(b) shows the rheological model of the geosynthetic element, on which a stress $\Delta\sigma$ is acting.



(a) Clogged geotextile under pressure



(b) Rheological model

Figure 2. Geotextile condition after construction.

It is assumed that the geotextile and clogging particles exhibit elastic behaviors. The cake, sedimented geotextile, and virgin geotextile can be represented by serial connection, and the sedimented geotextile by a parallel connection of sediments and geotextile. The total change in the thickness (T) under the stress change, $\Delta\sigma$ can be expressed as follows:

$$T = t_s + t_{sg} + t_g \tag{1}$$

$$\delta T = \delta t_s + \delta t_{sg} + \delta t_g = t_s \Delta\varepsilon_s + t_{sg}\Delta\varepsilon_{sg} + t_g \Delta\varepsilon_g \tag{2}$$

As t_g is the thickness of a horizontally wide element, the vertical strain can be assumed to be approximately equal to the volumetric strain.

$$\frac{\delta T}{T} = \Delta\varepsilon = \frac{t_s}{T}\Delta\varepsilon_s + \frac{t_{sg}}{T}\Delta\varepsilon_{sg} + \frac{t_g}{T}\Delta\varepsilon_g = \left[\frac{t_s}{T}\frac{1}{E_s} + \frac{t_{sg}}{T}\left(\frac{1}{E_s + E_g}\right) + \frac{t_g}{T}\frac{1}{E_g}\right]\Delta\sigma \tag{3}$$

where E_s and E_g are the elastic modulus of the clogging material and geotextile, respectively. ε_s, ε_{sg}, and ε_g are the strains of the sedimentation, infiltrated geotextile, and virgin geotextile, respectively. As the geotextile is restrained along the horizontal direction, it can be assumed that ε_h is 0 and $\varepsilon_v = \varepsilon$. The thickness ratios are defined given below.

$$\frac{t_s}{T} = \alpha,\ \frac{t_g}{T} = \beta \ and \ \frac{t_{sg}}{T} = 1 - (\alpha + \beta) \tag{4}$$

In addition, the relative strength ratio of the geotextile and clogging material are given.

$$\gamma = \frac{E_s}{E_g} \tag{5}$$

The following equation is obtained by substituting Eq. (3) into Eq. (4) and Eq. (5).

$$\Delta\varepsilon = \frac{\alpha + \beta\gamma^2 + \gamma}{\gamma^2 + \gamma}\frac{\Delta\sigma}{E_g} \tag{6}$$

Generally, the permeability coefficient of the ground material is related to the void ratio of the ground and can be expressed as $\log k = a + be_o$ (Chapuis 2004). The permeability change with respect to the change in the void ratio is $\Delta e = A\Delta\log k$ (Walker et al. 2012). The strain of the geotextile can be expressed in terms of the change in the void ratio as follows.

$$\Delta\varepsilon = \frac{-\Delta e}{1 + e_o} = \frac{bA\Delta\log k}{b - a + \log k_o} = \frac{\Delta\log k'}{\log k_o'} = \frac{\log k_o' - \log k_o^*}{\log k_o'} = 1 - \frac{\log k_o^*}{\log k_o'} \tag{7}$$

where a and b are constants, A is the permeability change index, k_o' and k' are the modified permeability parameters, and k^* is the reduced permeability of the geotextile under compression. The permeability coefficient of the geotextile under normal stress conditions can be derived by substituting Eq. (6) into Eq. (7).

$$k^* = k_o'^{\left(1 - \frac{\alpha + \beta\gamma^2 + \gamma}{\gamma^2 + \gamma}\frac{\Delta\sigma}{E_g}\right)} \tag{8}$$

The permeability coefficient of the geotextile k^* reflects the clogging behavior under stress change, and can be further simplified depending on the conditions.

When the geotextile is clogged, the degree of hydraulic deterioration can be evaluated using the concentration of the clogging material and the relationship between the concentration of the clogging material and the decrease in the permeability was found to be linear (Franks et al. 2012). The decrease in the permeability due to clogging can be expressed as follows.

$$k_o' = (1 - \lambda C)k_o \tag{9}$$

where k_o is the permeability of the virgin geotextile, k_o' is the permeability of the clogged geotextile, C is the weight ratio of the clogging material, and λ is the clogging coefficient. The change in k_o' depending on the type of clogging material can determined by the hydraulic deterioration characteristic of the geotextile. If loading and clogging occur simultaneously, Eq. (8) and Eq. (9) can be combined for the arbitrary concentration of sediments as follows.

$$k^* = \left[(1-\lambda C)\right] k_o^{\left(1-\frac{\alpha+\beta\gamma^2+\gamma}{\gamma^2+\gamma}\frac{\Delta\sigma}{E_g}\right)} \tag{10}$$

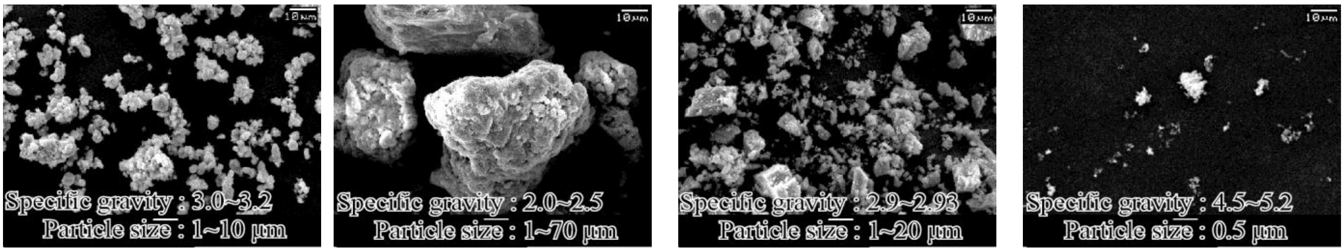
3 EXPERIMENTAL STUDY

3.1 *Materials*

3.1.1 *Clogging materials*

The main sediments of the tunnel drainage system are known to be white sediments comprising calcium oxide and calcium carbonate and red sediments containing large amounts of iron and soil particles (Woo 2005). Calcium oxide is a major component of cement. During tunnel construction grouts used for ground reinforcement flow into the tunnel with the groundwater, and are deposited. Meanwhile, calcium carbonate is formed due to the neutralization of concrete, and sedimentation occurs under slow groundwater flow conditions. Iron oxide is formed because of the corrosion of tunnel supports such as rebars, rock bolts, and steel pipes.

The main constituents of tunnel drain sediments were selected as the test materials to investigate the clogging behavior of the tunnel drainage system: calcium oxide (cement leaching), calcium carbonate (concrete neutralization), iron oxide (steel corrosion), and bentonite as the test materials. Figure 3 shows the images of each particles captured using scanning electron microscope (SEM) with a magnification of 1,000.



(a) CaO (b) Bentonite (c) $CaCO_3$ (d) Fe_2O_3

Figure. 3 Clogging particles in tunnel drainage system (SEM with a magnification of 1,000)

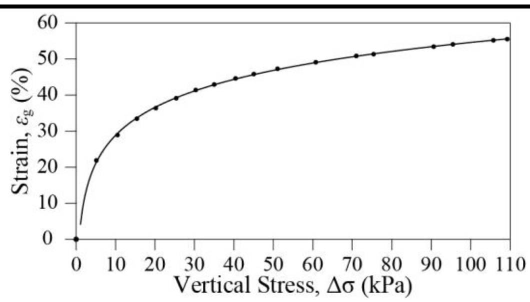
3.1.2 *Virgin geotextile*

The geotextiles used for the test are needle-punched geotextiles made of polyester (PE). Table 1 lists the basic physical properties of the geotextile used in this study.

Table. 1 Material property of Geotextile

mass per unit area μ_A(g/m^2)	thickness t_g (mm)	fiber diameter (μm)	tensile strength T(N)	
			length	width
420.2	3.7	27	2532.3	1600.6

95% filtration opening size(dry, ASTM D 4751/wet,ISO 12956): O_{95}(μm)		elongation ε(%)	
dry	wet	Length	Width
103	99	73.8	86.2



$$\varepsilon = 9.45836 \times \ln(\sigma) + 9.6185$$

* Notes : t_g= of GTX under 2kPa normal stress

A compression test was performed on the geotextile. The thickness of the geotextile was measured with the LVDT by applying a load using a steel plate of which width is 30 cm and a length is 15 cm. Test results are also included in Table 1.

3.2 *Clogging test*

3.2.1 *Test method*

The deposit characteristics of calcium oxide, calcium carbonate, bentonite, and iron oxide, which are the main sediments of the tunnel drainage system, were investigated. Figure 4 shows the clogging apparatus.

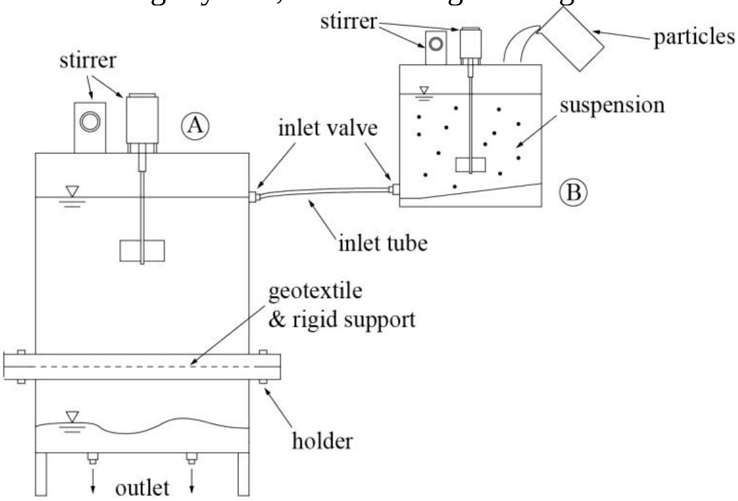


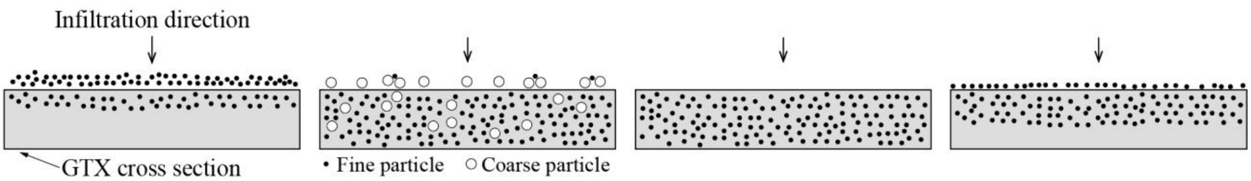
Figure. 4 Schematic diagram of clogging test apparatus

Two acrylic water tanks (A and B) equipped with a stirrer were employed to make the evenly mixed suspension. First, the geotextile having the same width as that of the steel porous plate was installed in the water tank A to immobilize the geotextile. The steel porous plate has thickness of 0.1 cm. The water level was maintained at 30 cm above the top of the geotextile, which was soaked for 2 hours or more without loading. Subsequently, the inlet valve was opened after mixing the clogging material with the water in the tank B for 30 min. Then, the sufficiently mixed suspension in tank B allows to flow into tank A. The deposit particle mass were measured by infiltrating the suspension into the geotextile for 2 hours while maintaining the water level of the tank A at a constant value.

The suspensions were prepared and tested by mixing the previously examined clogging particles with concentrations of 0.2, 0.5, 1, and 1.5%. The deposit mechanism was analyzed using SEM. Once the infiltration of the suspension was completed, the mass of the deposited particles in the geotextile after drying for 24 hours was measured.

3.2.2 *Clogging behavior*

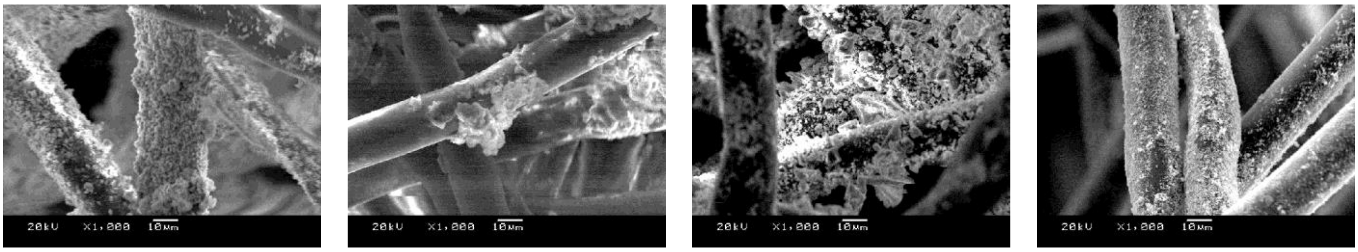
The deposit characteristics of each sediment observed in the test are shown in Figure 5. As $CaCO_3$ is a fine particle, most of the deposition occurred in the geotextile. Fe_2O_3 and CaO are heavy fine particles, some of which were deposited on the surface in the form of cakes. In the case of bentonite, fine grains were deposited within the geotextile pores, however larger grains were deposited on the surface. Calcium oxide and iron oxides, which have relatively low solubility in water, were partly deposited within the geotextile, and a cake is formed on the surface. On the other hand, calcium carbonate and bentonite, which have high solubilities, were deposited uniformly within the whole cross section of the geotextile.



(a) CaO (b) Bentonite (c) $CaCO_3$ (d) Fe_2O_3

Figure. 5 Depositional characteristics of clogging materials

Figure 6 shows the microscopic surface of the deposited geotextile for a 0.5% concentration clogging test samples were dried for 24 hours. Generally, in a soil–geotextile system, when the geotextile pore size is smaller than that of the soil particles, clogging occurs. In the samples used for the test, the pore size decreased and clogging increased because fine particles smaller than the pore size of the geotextile deposited in the geotextile adhered to the fiber surface and reduced the pore size. Although the number of infiltrating particles increased because of the increase in the suspension concentration, the mass of the deposited particles in the geotextile did not increase because the cake formation on the surface of the geotextile prevented further infiltration.



(a) CaO (b) Bentonite (c) $CaCO_3$ (d) Fe_2O_3

Figure. 6 Deposition of clogging materials on the geotextile fibers (SEM with a magnification of 1,000)

The clogged geotextile was dried for 24 hours, and the weight was measured. The clogging weight ratio (W_c) was calculated using Eq. (11).

$$W_c = \frac{W - W'}{W'} \times 100\,(\%) \tag{11}$$

where W' is weight of virgin geotextile, W is weight of geotextile after clogging test. Figure 7 shows the variation in the clogging weight ratio (W_c) with respect to the change of the suspension concentration. The greater the number of clogging particles infiltrating the geotextile, the greater is the mass of the deposited particles in the geotextile. However, for a concentration of 1.0% or more, the mass of the deposited particles in the geotextile was largely constant. The maximum clogging weight ratio was approximately 35% of the calcium oxide, which has a low solubility, and approximately 150% of the iron oxide, which has the smallest particle size.

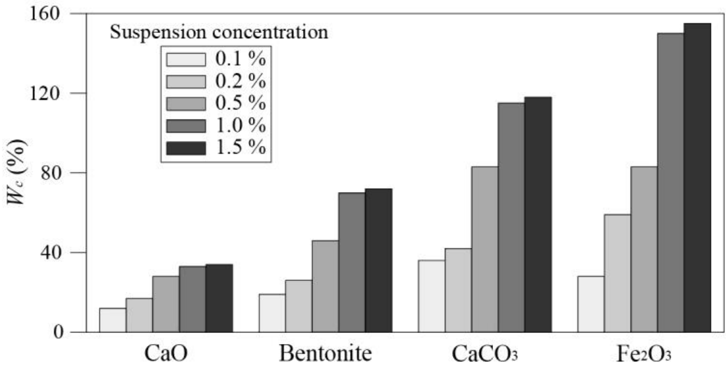


Figure. 7 Clogging weight ratio with the suspension concentration

3.3 *Permeability test*

3.3.1 *In-plane permeability test*

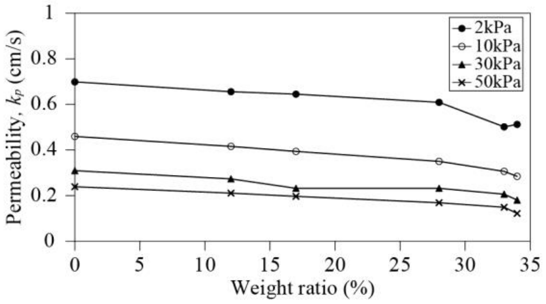
An in-plane permeability test was conducted in accordance with the ASTM D4716-08 to investigate the effect of clogging of the geotextile. The geotextile samples clogged in 6 cases of the clogging weight ratio were tested for a vertical load. The permeability was measured at the same hydraulic gradient of 1.0. The range of the vertical load was set to 2–50 kPa.

If an in-plane flow occurs in the geotextile, the cross-sectional area of the flow is the cross section of the geotextile. Accordingly, the in-plane permeability, k_p can be calculated using Eq. (12).

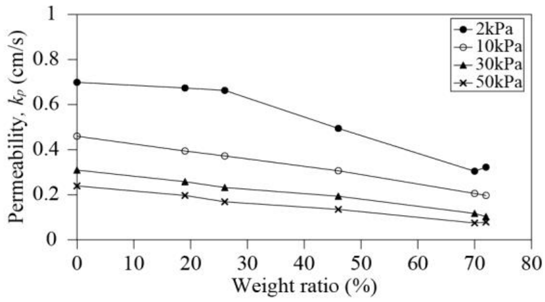
$$k_p = \frac{Q \cdot L}{B \cdot T \cdot \Delta h} \tag{12}$$

where Q is the flow rate through the geotextile, L is the length of the geotextile, B is the width of the geotextile, and Δh is the hydraulic gradient of each end of the geotextile.

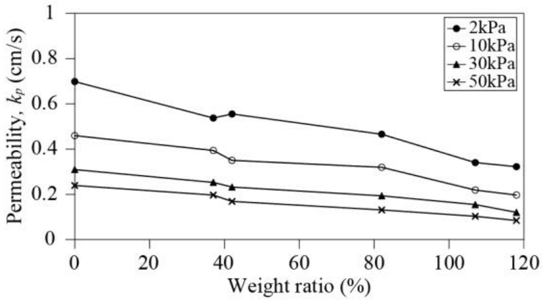
Figure 8 shows the permeability test results with different suspension concentrations and stress. With the increase in the mass of the deposited particles in the geotextile, the decrease rate of the permeability increased. The sample with the highest clogging weight ratio is iron oxide, however the highest decrease rate of permeability was the geotextile clogged by bentonite. This is because the specific gravity of iron oxide is relatively high in comparison with the volume occupied in pores of the geotextile. This implies that the change in the pore size of the geotextile is more important than the mass of the deposited particles in the clogging of the geotextile. The permeability coefficients of the geotextile decreased by 56, 54, 49% and 28% in case of bentonite, calcium carbonate, iron oxide and calcium oxide respectively. It is found that the in-plane permeability of the geotextile decreased by up to approximately 56% because of the clogging, by up to approximately 65% because of the load, and by up to approximately 90% considering both the load and clogging.



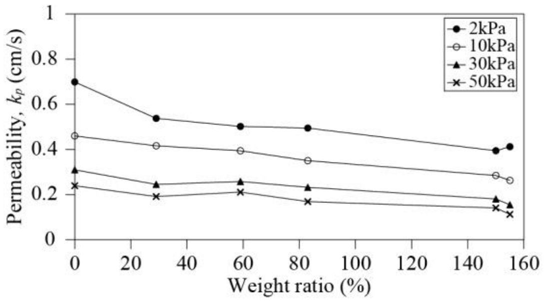
(a) CaO



(b) Bentonite



(c) $CaCO_3$



(d) Fe_2O_3

Figure. 8 In-plane permeability of the geotextile with respect to the clogging weight ratio

3.3.2 *Validation of theoretical model*

The applicability of the permeability model, derived in Section 2, was analyzed using the test results. The in-plane permeability of the geotextile affected by clogging was obtained, as shown in Figure 8. The permeability change due to the stress increase on the clogged geotextile can be expressed using Eq. (10). It is assumed that the particles deposited in all cross sections with in geotextile. The elastic modulus of the soil structure was assumed to be 1/10 of the geotextile considering the dispersed structure of the particles. Accordingly, the clogged in-plane permeability can be simply reduced as follows.

$$k^* = \left[\left(1 - \lambda C\right) k_o \right]^{\left(1 - \frac{\Delta\sigma}{(\gamma+1)E_g}\right)} \tag{13}$$

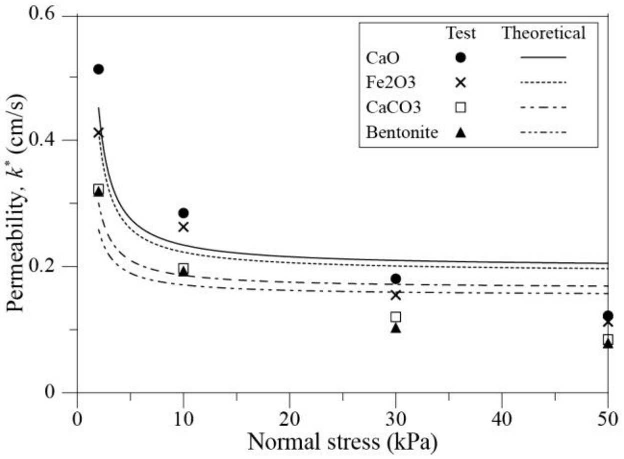


Figure. 9 Validation of proposed permeability degradation model

Figure 9 compares the experimental results and proposed permeability degradation model of Eq. (13). The theoretical predictions and the experimental results show a similar decreasing tendency in the permeability; however, the theoretically predicted in-plane permeability is somewhat higher. The difference between the theoretical prediction and experimental results increases with the stress increase; however, the difference is not significant. The proposed theoretical permeability model can be applied to approximately evaluate the hydraulic deterioration of tunnel drainage system.

4 CLONCLUSIONS

Hydraulic deterioration mechanism of the tunnel drainage system was investigated using specially devised clogging test apparatus. Specific clogging materials observed in the tunnel drainage system were chosen: calcium oxide, calcium carbonate, bentonite, and iron oxide. It is shown that the higher the particle concentration of the inflow water, the greater is the mass of the deposited particles in the geotextile. Calcium oxide, which has a low solubility in water, was least deposited in the geotextile, whereas iron oxide, which has a high specific gravity, showed the highest mass of deposited particle.

The effect of hydraulic deterioration is investigated by performing in-plane permeability test. It is found that the in-plane permeability of the geotextile decreased by up to approximately 90% considering both the load and clogging. Permeability degradation model for tunnel drainage system is proposed based on geo-hydraulic behavior. The model considers the hydraulic deterioration characteristics combining squeezing and clogging in the tunnel drainage system. The predictions using the proposed geo-hydraulic permeability model was generally consistent with the experimental results.

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