

HYDRAULIC CONDUCTIVITY OF NONPREHYDRATED GEOSYNTHETIC CLAY LINERS PERMEATED WITH INORGANIC SOLUTIONS AND WASTE LEACHATES

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ABSTRACT

To investigate systematically the effects of electrolytic solutions on the barrier performance of geosynthetic clay liners (GCLs), a long-term hydraulic conductivity test for 3 years at longest was conducted on a nonprehydrated GCL permeated with inorganic chemical solutions. The hydraulic conductivity test for waste leachates was also conducted. The results of the test show that the hydraulic conductivity of GCLs significantly correlates with the swelling capacity of bentonite contained in GCLs. GCLs have excellent barrier performance of $k < 1.0 \times 10^{-8}$ cm/s when the free swell is larger than 15 mL/2 g-solid regardless of the type and concentration of the permeant solution. In addition, when the results of the hydraulic conductivity test with chemical inorganic solutions were compared to those with waste leachates, the hydraulic conductivity of GCL permeated with chemical solution was almost the same within the electric conductivity of 0–25 S/m as that permeated with waste leachate having similar electric conductivity. The hydraulic conductivity of GCLs to be used in landfill bottom liners can be estimated by the hydraulic conductivity values obtained from the experiment using chemical solutions having the similar electric conductivity values, if the chemical solution had the electric conductivity within = 25 S/m.

Key words: bentonite, chemical compatibility, geosynthetic clay liner, hydraulic conductivity, long-term hydraulic conductivity test (IGC: D4)

INTRODUCTION

Geosynthetic clay liners (GCLs) are effective barrier materials alternated or combined with compacted clay layers, which are mainly used as the component of present bottom liner systems in waste containment facilities because of their relatively low cost, easy installation, and excellent barrier performance to water. GCLs are factory-manufactured clay liners consisting of a thin layer of sodium or calcium bentonite glued to a geomembrane or encased by geotextiles. The barrier performance of GCLs is attributed to the swelling of bentonite contained in GCLs. Sodium bentonite swells more than calcium bentonite, and shows the low hydraulic conductivity value of $k < 1.0 \times 10^{-8}$ cm/s to water (Gleason et al., 1997; Egloffstein, 2001; Egloffstein, 2002). However, the exchangeable cation contained in a leachate from waste containment facilities obstructs the swelling of the bentonite, and deteriorates the barrier perform-

ance of GCLs (e.g. Egloffstein, 1995). Therefore, the barrier performance and chemical compatibility of GCLs against electrolytic solutions must be evaluated so that measures can be taken to prevent toxic contaminants from leaking to the outside of waste containment facilities.

The effects of aggressive inorganic solutions on the barrier performance and swelling of bentonite have been researched (e.g. Petrov and Rowe, 1997; Ruhl and Daniel, 1997; Shackelford et al., 2000; Jo et al., 2001; Shan and Lai, 2002; Katsumi et al., 2004; Kolstad et al., 2004a). These studies conclude that the hydraulic conductivity and swelling capacity of bentonite is sensitive to the concentration and ionic valence of cation in a permeant solution, in particular, an electrolyte first exposed to bentonite dominantly affects the hydraulic conductivity value in an ultimate state. In addition, a permeant solution having a lower concentration requires a longer testing duration to stabilize the hydraulic

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The manuscript for this paper was received for review on December 1, 2005; approved on July 26, 2006.

Written discussions on this paper should be submitted before September 1, 2007 to the Japanese Geotechnical Society, 4-38-2, Sengoku, Bunkyo-ku, Tokyo 112-0011, Japan. Upon request the closing date may be extended one month.

conductivity value of the bentonite. A CaCl_2 solution having a molar concentration of <0.02 M increased gradually the hydraulic conductivity of GCLs from 1.0×10^{-9} cm/s to 1.0×10^{-8} cm/s in 1–3 years (Shackelford et al., 2000; Lee and Shackelford, 2005b).

In most previous studies, the permeant solution used for the hydraulic conductivity test was composed of single-species of NaCl or CaCl_2 , which is mainly contained in real leachate from waste containment facilities. Thus, most previous studies have been confined to evaluations from the aspect of the single-species solution. Kolstad et al. (2004a) investigated the hydraulic conductivity of GCL permeated with the multi-species solution of LiCl– CaCl_2 , NaCl– MgCl_2 or LiCl–NaCl– CaCl_2 – MgCl_2 . However, there are still so few reports regarding the hydraulic conductivity for the multi-species solution that the barrier performance of GCLs against electrolytic solutions having a complex component like waste leachate cannot be systematized quantitatively. Therefore, the hydraulic conductivity for the multi-species solution must be further investigated. It is also important to investigate whether the barrier performance of GCL exposed by waste leachate having various chemical substances can be estimated from the results of previous studies in which permeant solutions easily made of inorganic substances such as NaCl and CaCl_2 were used. Although Ruhl and Daniel (1997) conducted a hydraulic conductivity test with a waste leachate, the test duration was short and only one kind of waste leachate was used. There have also been very few reports regarding the hydraulic conductivity for waste leachate. To secure the barrier performance of GCLs that will be applied to a real site, the hydraulic conductivity of GCLs for electrolytic solutions (in particular, the multi-species solution or waste leachate) must be further investigated. In addition, it is necessary to systematize the barrier performance against electrolytic solutions and to discuss the adequacy of the hydraulic conductivity test with a chemical solution such as a NaCl or a CaCl_2 solution, which have been used in previous studies.

This study investigates systematically the effects of electrolytic solutions on the barrier performance of GCLs, and discusses the applicability of the hydraulic conductivity test with a chemical solution as the prediction method of barrier performance that will be exhibited in a real site. This paper shows the results of the long-term hydraulic conductivity test on a nonprehydrated GCL permeated with two types of solutions as follows; (1) the chemical solutions that consisted of the single-species and multi-species of NaCl, CaCl_2 , or KCl, and (2) the real leachates sampled from waste containment facilities in Japan. The hydraulic conductivity test with these permeant solutions was continuously conducted for 3 years at longest to achieve the chemical compatibility pointed by Shackelford et al. (1999 and 2000), and the difference in the hydraulic conductivity values for the chemical solution and the waste leachate was investigated.

SWELLING AND HYDRAULIC BARRIER OF BENTONITE

Development of Swelling and Hydraulic Barrier

Bentonite is primarily composed of the mineral montmorillonite, which is a member of the smectite family (Grim, 1968). Montmorillonite is composed of layers where a thin crystal interlayer (which thickness is approximately 9.8 Å in desiccation state) consisting of two silica tetrahedral sheets and one alumina octahedral sheet is accumulated. A trivalent Al contained in the octahedral sheet is partially replaced with a divalent Mg or Fe so that this crystal layer has a permanent charge deficiency. To supplement this charge deficiency, there is a hydrated exchangeable cation (e.g. Na, K, Ca, Mg) between the crystal layers. Montmorillonite has a large specific surface area ($770 \text{ m}^2/\text{g}$), a high cation exchange capacity (60–100 meq/100 g), and a high charge deficiency (0.7 – $1.3 \mu\text{eq}/\text{m}^2$). These factors contribute to the high swelling potential and low hydraulic conductivity of bentonite to water. Bentonite used in GCLs typically has montmorillonite contents of 65–90% (Shackelford et al., 2000).

The correlation between the hydraulic conductivity and the swelling capacity of bentonite is generally attributed to the volume of water molecules that are bound to the clay surface. These water molecules are considered the immobile water phase which behaves like the solid phase obstructing the flow. When the volume of bound water molecules increases and the immobile water phase becomes thick, the effective pore space comprised of freely flowing water decreases. At the macro-scale, an increase in the bound water means a decrease in the hydraulic conductivity of bentonite (Lagerwerff et al., 1969; Mesri and Olson, 1971). The volume of bound water has traditionally been described in the electric diffusion double layer using the Stern-Gouy theory (Lambe, 1958; Mitchell, 1993; Shang et al., 1994). However, Stern-Gouy theory has significant limitations and does not accurately describe the crystal interlayer expansion, which is called the swelling (Norrish, 1954; Sposito and Prost, 1982; Low, 1987; Sposito, 1989; McBride, 1994).

The hydraulic barrier of bentonite significantly correlates with the crystal interlayer expansion of montmorillonite by the intercalation of water molecules. There are two types in the interlayer expansion of montmorillonite; the osmotic swelling and the hydration swelling (van Olphen, 1977; McBride, 1994; Prost et al., 1998). The osmotic swelling occurs when the exchange sites in the interlayer contain monovalent cations (Norrish and Quirk, 1954; Posner and Quirk, 1964; Low, 1987; Chang et al., 1995; Karaborni et al., 1996). If the exchange sites are occupied with monovalent cations, the force where the monovalent cations attract the interlayer charging with negative electricity is weak so that water molecules are easily intercalated. The space of crystal interlayers of montmorillonite expands with water molecules (>40 Å), and the bound water in bentonite is increased with high

Table 1. Review on hydraulic conductivity tests of geosynthetic clay liners (GCLs)

Reference	Type of GCL	Solution	Special testing conditions noted
Egloffstein (2001)	GCL (Geotextile-sandwiched bentonites)	DI water, CaCl ₂	Prehydration, Na bentonite, Ca bentonite, Sequence of permeation
Jo et al. (2001)	GCL (Geotextile-sandwiched granular bentonites)	DI water, LiCl, NaCl, KCl, CaCl ₂ , MgCl ₂ , ZnCl ₂ , CuCl ₂ , LaCl ₃ , Base, Acid	
Katsumi et al. (2004)	GCLs (Geotextile-sandwiched granular or powdered bentonites), Modified bentonite	DI water, NaCl, CaCl ₂ , NaCl-CaCl ₂	Prehydration
Katsumi and Fukagawa (2005)	GCLs (Geotextile-sandwiched granular or powdered bentonites)	DI water, NaCl, CaCl ₂ , NaCl-CaCl ₂ , MSW leachate	Confining stress
Kolstad et al. (2004a)	GCL (Geotextile-sandwiched granular bentonites)	LiCl-CaCl ₂ , NaCl-MgCl ₂ , LiCl-NaCl-CaCl ₂ -MgCl ₂	
Kolstad et al. (2004b)	GCL (Geotextile-sandwiched granular bentonites), Dense-prehydrated GCL	DI water, NaCl, CaCl ₂ , Base, Acid	
Lee and Shackelford (2005a)	GCL (Geotextile-sandwiched granular bentonites)	CaCl ₂	Prehydration
Lee and Shackelford (2005b)	GCL (Geotextile-sandwiched granular bentonites)	DI water, CaCl ₂	
Petrov and Rowe (1997)	GCL (Geotextile-sandwiched granular bentonites)	NaCl, Synthetic MSW leachate	Confining stress, Prehydration
Ruhl and Daniel (1997)	GCL (Geotextile-sandwiched granular bentonites)	Tap water, Base, Acid, Synthetic leachates, MSW leachate	
Shackelford et al. (2000)	GCL (Geotextile-sandwiched granular bentonites)	CaCl ₂	
Shan and Lai (2002)	GCL (Geotextile-sandwiched granular bentonites)	DI water, Tap water, Acid, Sea water, MSW leachate	
Vasko et al. (2001)	GCL (Geotextile-sandwiched granular bentonites)	CaCl ₂	Prehydration

density. The osmotic swelling provides the excellent hydraulic barrier to bentonite. On the other hand, the hydration swelling appears in bentonite containing multivalent cations (Norrish and Quirk, 1954; Posner and Quirk, 1964; Kjellander et al., 1988; Prost et al., 1998). The intercalation of water molecules is limited and the space of crystal interlayers is narrow, because multivalent cations attract the crystal interlayer more strongly than monovalent cations. Therefore, the hydration swelling cannot sufficiently provide the swelling and hydraulic barrier to bentonite. Egloffstein (1995) measured the free swell of sodium bentonite (the exchange sites are occupied with sodium ions) and calcium bentonite (the exchange sites are occupied with calcium ions), and showed over 30 mL/2g-solid for sodium bentonite and 5–7 mL/2g-solid for calcium bentonite, respectively.

The swelling capacity and hydraulic barrier of bentonite significantly correlates the space of the crystal interlayers expanded by the intercalation of water molecules. When the exchange sites are occupied with cations having the stronger attraction force, the space of the crystal interlayers is narrower because water molecules are not intercalated easily. Therefore, if bentonite is permeated with electrolytic solution having stronger concentration, the bentonite cannot swell sufficiently and cannot form the superior hydraulic barrier.

Factors Affecting the Hydraulic Conductivity of Bentonite

Table 1 shows the review of previous studies on the hydraulic conductivity tests of GCLs. Fundamental factors affecting the hydraulic conductivity of GCLs are (1) quality of bentonite, (2) effective pressure confining GCLs, and (3) concentration and type of chemical substances dissolved in permeant solution. The quality of bentonite used in GCLs is affected by several factors; the mineralogical composition (in particular, montmorillonite content), the surface area and particle grain size, the surface charge deficiency, the cation exchange capacity, and the composition and amount of exchangeable cations (in particular, sodium cation). The quality of bentonite is substantially dependent on the mining site and the crushing process of the bentonite. In general, the superior barrier performance of GCLs is provided by the bentonite having the higher quality such as higher montmorillonite content, smaller surface area and particle grain size, higher surface charge deficiency, higher cation exchange capacity, and larger amount of exchangeable sodium cation. Lee and Shackelford (2005b) investigated the impact of bentonite quality, which differed in the montmorillonite contents (77 and 86 % in principal minerals of the bentonite), on the hydraulic conductivity of GCLs, and showed that the high bentonite quality decreased the hydraulic conductivity for

water but adversely increased the hydraulic conductivity for electrolytic solutions. Katsumi and Fukagawa (2005) compared the granular bentonite GCLs with the powdered bentonite GCLs in the hydraulic conductivity, and showed that the significant difference appeared in the hydraulic conductivity of GCLs permeated with strong electrolytic solution. The powdered bentonite GCLs was more chemically compatible than the granular bentonite GCLs.

Second factor, effective pressure confining GCLs, significantly affects the hydraulic conductivity of GCLs. GCLs that will be applied in bottom liners at waste containment facilities are confined by the load of the wastes buried. The confined pressure consolidates the bentonite so that the hydraulic conductivity of GCLs is decreased. Studts et al. (1996) investigated the effects of the confined pressure on the void ratio of sodium bentonite permeated with electrolytic solutions that are composed of different ionic valence. In addition, Katsumi and Fukagawa (2005) conducted the hydraulic conductivity tests on the powdered bentonite GCLs confined at 0–1256 kPa. Their researches showed that multivalent cations more significantly decreased the void ratio of bentonite or the hydraulic conductivity of GCLs by the confined pressure than monovalent cations.

Lastly, the concentration and type of permeant solution are also an important factor affecting the hydraulic conductivity of clay liners including GCLs. Strong acids and bases decrease the swelling capacity of bentonite, and increase the hydraulic conductivity of GCLs (Jo et al., 2001). Strong acids promote the dissolving of carbonates, iron oxides, and alumina octahedral sheets of clay minerals. Strong bases promote the dissolving of silica tetrahedral sheets of clay minerals. These effects increase the hydraulic conductivity, but reprecipitation of the dissolved compounds might clog the pore of bentonite and decrease the hydraulic conductivity of clay liners (Mitchell and Madsen, 1987). Nonpolar fluids or polar fluids having low dielectric constants such as alcohols are also a factor to increase the hydraulic conductivity of clay liners (Shackelford et al., 2000). However, no significant increase in the hydraulic conductivity occurs when the concentration of organic chemical compounds is lower than 50%, because the dilution with water increases the dielectric constant (Mesri and Olson, 1971; Bowders and Daniel, 1987; Fernandez and Quigley, 1988; Shackelford, 1994). In addition, an increase in the hydraulic conductivity by the permeation of electrolytic solutions is of great concern to use GCLs in the sea areas or waste containment facilities. When the electrolytic solution containing exchangeable cations permeates into GCLs, the space of crystal interlayers of clay minerals (in particular, montmorillonite) is narrowed by the attraction force of the cations, and the swelling volume and the barrier performance of bentonite are decreased. In the cases of the electrolytic solution having the multivalent exchangeable cations, moreover, the multivalent cations replace the monovalent cations occupied in the exchange sites of montmorillonite so that the barrier performance

Table 2. Properties of bentonite in GCL used

Property	Unit	Standard	Powdered bentonite in GCL
Soil particle density	[g/cm ³]	JIS A 1202	2.839
Natural water content	[%]	JIS A 1203	10.0
Plastic limit	[%]	JIS A 1205	51.0
Liquid limit	[%]	JIS A 1205	619.5
Swell index	[mL/2 g-solid]	ASTM D5890	33.0
Methylene blue consumption	[mmol/100 g]	JBAS 107 91	104.0
Chemical composition		JIS M 8853	
SiO ₂	[%]		59.65
Al ₂ O ₃	[%]		18.29
Fe ₂ O ₃	[%]		7.15
TiO ₂	[%]		0.41
CaO	[%]		2.02
MgO	[%]		3.14
K ₂ O	[%]		0.46
Na ₂ O	[%]		2.60
P ₂ O ₅	[%]		0.13
MnO	[%]		0.01
Ignition loss	[%]		6.15

are further decreased. The previous researches showed that the hydraulic conductivity of GCLs became higher for the electrolytic solution having the stronger concentration. The multivalent cation increased the hydraulic conductivity more significantly than the monovalent cation according to the comparison that was scaled by the molar concentration of the electrolytic solution (Lutz and Kemper, 1958; McNeal et al., 1966; Alther et al., 1985; Gleason et al., 1997; Petrov and Rowe, 1997; Ruhl and Daniel, 1997; Shackelford et al., 2000; Jo et al., 2001; Shan and Lai, 2002; Katsumi, et al. 2004; Kolstad et al., 2004a). However, most previous studies have been confined to evaluations from the aspect of the single-species solution of NaCl or CaCl₂, and little studies were reported on the multi-species solution (Kolstad et al., 2004a; Katsumi and Fukagawa, 2005). It is necessary to evaluate the hydraulic conductivity of GCLs permeated with the multi-species solution or the waste leachate in order to systematize quantitatively the chemical compatibility.

EXPERIMENTAL METHODS

Materials Used

GCL (Bentofix NPS 4900-1) was used in evaluating barrier performance against chemical attack. This is a typical GCL where the powdered sodium bentonite is encapsulated between a polypropylene woven geotextile and a polypropylene nonwoven geotextile by needle-punching fibers. The mass per unit area of GCL was approximately 4.73 kg/m², and the initial thickness was 6.0–7.0 mm. The basic properties of these materials are summarized in Table 2. The evaluations of these properties were based on Japanese Industrial Standards except for the methylene blue consumption and the swell index.

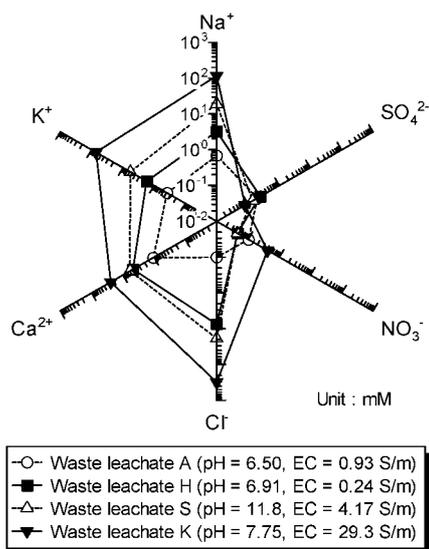


Fig. 1. Chemical component of waste leachates

Permeant Solutions

There were two types of permeant solutions used; (1) the inorganic chemical solutions and (2) the waste leachates.

The chemical solutions consisted of the single-species or multi-species of the inorganic chemical substances; NaCl, CaCl₂, and KCl. The ionic strength, I , and the ratio of monovalent to divalent, RMD , were used as indicators of the chemical solution. The ionic strength I is calculated from $I = 0.5 \sum c_i z_i^2$, where c_i and z_i are the concentration and the valence of the i -th ion, respectively. The ionic strength was calculated using only the cations contained in the chemical solution because the swelling and barrier performance (in particular, the development of the electric diffusion double layer) of bentonite are significantly dependent on the exchangeable cation. The other parameter, ratio of monovalent to divalent RMD , is calculated from $RMD = c_M / (2c_D)^{0.5}$, where c_M and c_D are the concentration of monovalent and divalent cations. The chemical solutions used in this study were prepared by parametrically changing these two parameters.

The waste leachates used in this study were sampled from 4 waste containment facilities (A, H, S, and K) in Japan. The chemical component in each waste leachate is shown in Fig. 1. This component showed the chemical substances that were detectable with Sequential Plasma Spectrometer (ICPS-8000; Shimadzu Co., Ltd.) and Ion Chromatography (PIA-1000; Shimadzu Co., Ltd.). Many other chemical substances would be contained in each waste leachate besides the substances shown in this figure. The waste leachate S had a high pH value, and the waste leachate K had a high electric conductivity.

Free Swell Test

A free swell test was performed according to ASTM D 5890 "Standard Test Method for Swell Index of Clay Mineral Component of Geosynthetic Clay Liners". The

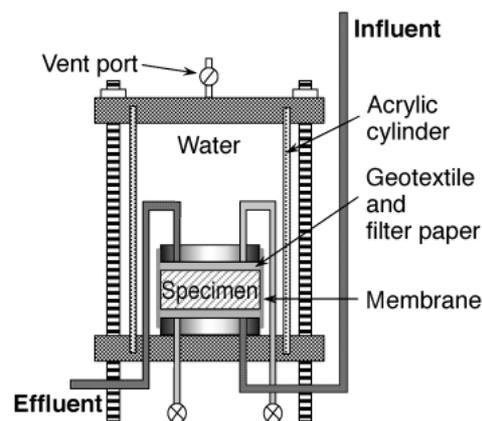


Fig. 2. Apparatus for the hydraulic conductivity test using flexible-wall permeameters: GCL specimen was 6 cm in the diameter, and approximately 0.7 cm in the thickness

soil material used in this test was the powdered bentonite obtained from GCL. Two grams of the dry powdered bentonite was dusted into a permeant solution in a 100 mL graduated cylinder filled with 90 mL solution. After these 2 g of bentonite were placed into the graduated cylinder, this cylinder was filled up to 100 mL. The graduated cylinder was carefully covered without disturbance. The sample stood for 24 hours before taking a reading.

Liquid Limit Test

The soil material used in the liquid limit test was the powdered bentonite obtained from GCL. After the bentonite was soaked with a permeant solution for 1 day, the liquid limit test was conducted according to JIS A 1205. The bentonite soaked with a solution was covered by lapping with a polyethylene sheet so that the moisture in the sample could not evaporate during the test.

Hydraulic Conductivity Test

The powdered bentonite GCL was used for the hydraulic conductivity test. The hydraulic conductivity test was conducted according to ASTM D 5084 "Standard Test Methods for Measurement of Hydraulic Conductivity of Saturated Porous Materials Using a Flexible Wall Permeameter". The test was performed by using flexible-wall permeameters with a cell pressure of 20–30 kPa and an average hydraulic gradient of 90 in a constant temperature room controlled at 20 degrees. The apparatus for the test is shown in Fig. 2.

The procedure was as follows. In order to make the specimen for the test, GCL was cut to a diameter of 6 cm. The GCL used was approximately 7 mm in thickness, 0.87 g/cm³ in bulk dry density, and 10% in water content. Next, the specimen was sandwiched with the filter papers and the woven geotextiles, and was placed in the apparatus. The side of this specimen was restrained with a rubber membrane. This membrane received a hydraulic pressure of 20–30 kPa by filling an outside cell with water, so that the solution could permeate through the specimen without a leakage on the side of the specimen. For the specimen permeated with chemical solutions, the

solutions were directly permeated from the influent point without prehydration with the deionized water. The test was continuously performed for 3 years at longest in order to investigate the long-term change in hydraulic conductivity and to achieve the chemical compatibility. The flow volumes, the thickness and the hydraulic conductivity of the specimen were measured over the testing duration.

Results

Free Swell

Figure 3 shows the results of the free swell test with the chemical solutions. This figure indicates the relation between the free swell of the bentonite and the ionic strength of the chemical solutions. “Na(X) : K(Y)” shown in this figure means the mixing of volumetric ratio NaCl solution and KCl solution. For example, “Na(2) : K(8)” indicates that NaCl solution and KCl solution were mixed under the volumetric ratio NaCl : KCl = 2 : 8. The open plots show the free swell for the deionized water and the single-species solution, and in contrast, the closed

plots show the free swell for the multi-species solution. As the global trend, the free swell of the bentonite was smaller for the solution having the stronger ionic strength. The free swell of the bentonite became approximately 7 mL/2 g-solid when the ionic strength of the chemical solution exceeded 0.5 M. For the effects of the difference in the type of cation, the solution containing KCl affected a greater decrease of the free swell for the same ionic strength levels than any other solution containing NaCl or CaCl₂. The free swell for the single-species solution of KCl was approximately a half of that for the single-species solution of NaCl. Figure 4 shows a free swell of the bentonite for the various permeant solutions of $I=0.1$ M. This figure shows that the electrolytic solution obstructs the swelling of the bentonite. Also, the single-species solution of KCl obstructs more seriously the swelling of the bentonite than the single-species solution of NaCl. Therefore, the effect of the electrolytic solutions on the free swell is different even when the valence and ionic strength is the same in each solution.

Next, Fig. 5 shows the results of the free swell test with the waste leachates. Figure 5(a) indicates the free swell values for the waste leachates A, H, S, and K. The waste

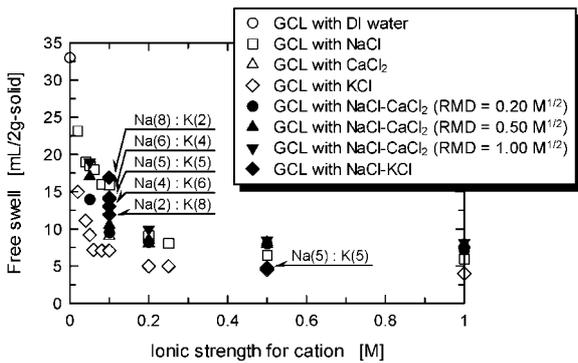


Fig. 3. Relation between the free swell and the ionic strength for chemical solution: “Na(X):K(Y)” shown in this figure means the mixing volumetric ratio of NaCl solution and KCl solution: For example, “Na(2):K(8)” indicates that NaCl solution and KCl solution were mixed under the volumetric ratio NaCl:KCl = 2:8

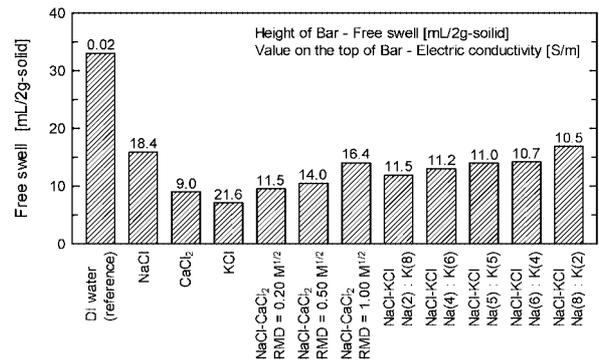
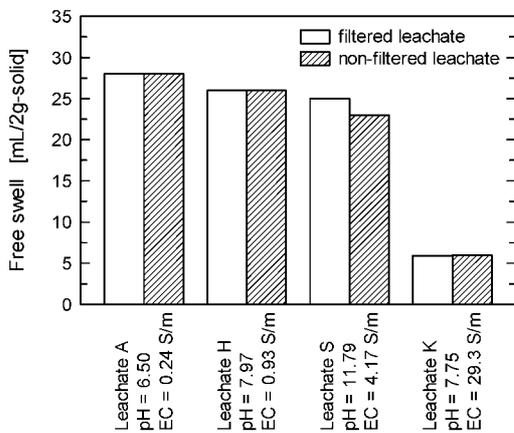
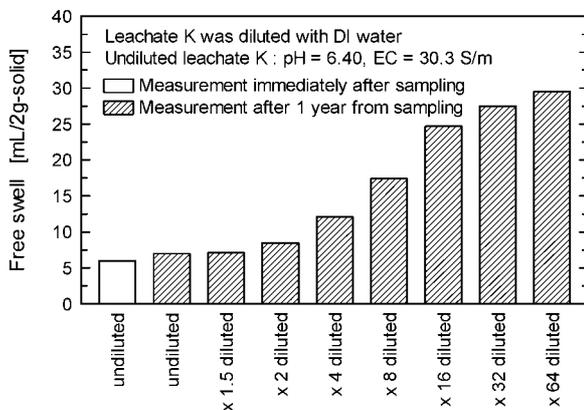


Fig. 4. Effect of the electrolytes on the free swell of powdered bentonite in GCL under $I=0.1$ M



(a) Waste leachates A, H, S, and K



(b) Waste leachate K and its diluted solutions

Fig. 5. Free swell of powdered bentonite in GCL for waste leachate

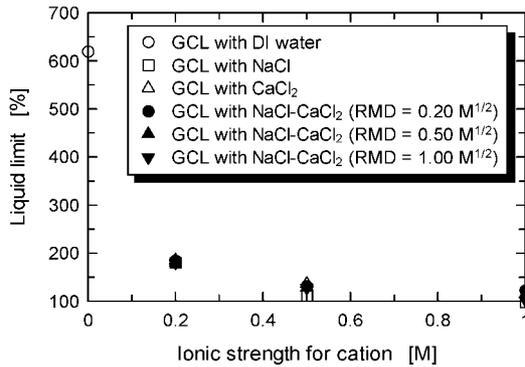


Fig. 6. Relation between the liquid limit and the ionic strength for chemical solution

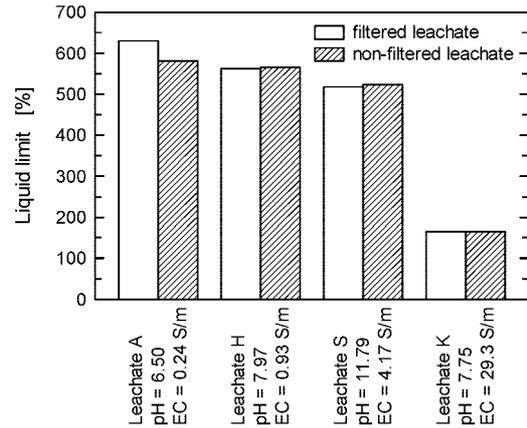


Fig. 7. Liquid limit of powdered bentonite in GCL for waste leachate

leachates with and without filtration were used. The filtration was conducted by using $6\ \mu\text{m}$ mesh filter paper. The free swell of the bentonite was the same regardless of the filtration of the waste leachate, and was significantly dependent on the electric conductivity of the waste leachate. The free swell shows the lower value for the waste leachate having the higher electric conductivity. Figure 5(b) indicates the free swell values for waste leachate K and its diluted solutions. The open bar indicates the free swell that was measured immediately after sampling, and in contrast, the hatched bar indicates the free swell that was measured after an interval of 1 year from sampling. The waste leachate immediately after sampling obstructed the swelling of the bentonite more slightly than the waste leachate that was left alone for 1 year. Also, the waste leachate diluted with the deionized water increased the free swell because the concentration of the solution was decreased by dilution. Taking these findings together, the swelling capacity of the bentonite becomes lower for an electrolytic solution having the stronger concentration.

The electrolytic solution obstructed the swelling of the bentonite for the following reasons. The electric diffusion double layer of bentonite becomes thinner by attracting the stronger electrolyte (Mitchell, 1993). The double layer is the immobile water layer formed by attracting water molecules to the surface of a montmorillonite mineral with an electrostatic gravitation. The thickness of this layer is significantly related to the swelling capacity and barrier performance of bentonite. When pure water comes in contact with a montmorillonite mineral, the immobile water layer becomes thick by attracting the water molecules to the montmorillonite mineral, then the bentonite swells. However, when water including electrolytes such as NaCl or CaCl_2 comes in contact with a montmorillonite mineral, the immobile water layer becomes thin because the electrolytes are attracted to the montmorillonite mineral together. Therefore, the swelling capacity of bentonite deteriorates for the electrolytic solution.

Liquid Limit

The swell and the hydraulic conductivity of a soil

material can be investigated approximately by evaluating the liquid limit, which indicates how much water can be held in a soil. Figure 6 shows the results of the liquid limit test with the chemical solutions. This figure indicates the relation between the liquid limit of the bentonite and the ionic strength of the chemical solutions. The liquid limit of the bentonite contained in GCL decreased when the bentonite was exposed to the strong electrolytic solution. For the effect of the difference in the type of cation on the liquid limit, the difference in the type of cation dissolved in the permeant solution did not appear clearly on the liquid limit value.

Figure 7 shows the results of the liquid limit test with the waste leachates. The filtration of the waste leachate hardly affected the liquid limit value of the bentonite, and the liquid limit was decreased for waste leachate having high electric conductivity.

Hydraulic Conductivity

The changes of the hydraulic conductivity over time are shown in Figs. 8 to 18. These figures show the changes of (1) the hydraulic conductivity, k , (2) the thickness of specimen, H , and (3) the volumetric flow ratio, $Q_{\text{out}}/Q_{\text{in}}$, to the pore volumes of flow, PVF . Here, the pore volumes of flow, PVF , is the dimensionless parameter regarding the elapsed time, and this parameter is a value in which the accumulated flow volume is divided by the porous volume of the specimen. Figures 8 to 15 shows the results on the powdered bentonite GCL permeated with the chemical solutions. On the other hand, Figs. 16 to 18 shows the results on the powdered bentonite GCL permeated with the waste leachates.

Figures 8 to 10 show the results of the hydraulic conductivity test with the single-species solutions of NaCl, CaCl_2 and KCl, respectively. The closed plots indicate the case of using the deionized water, in contrast, the open plots indicate the cases of using the electrolytic solutions. The hydraulic conductivity of the powdered bentonite GCL was very low: $k = 2.2 \times 10^{-9}\ \text{cm/s}$ for the deionized water. However, the hydraulic conductivity of GCL became higher for the electrolytic solutions having stronger ionic strength. As shown in Fig. 8, the hydraulic

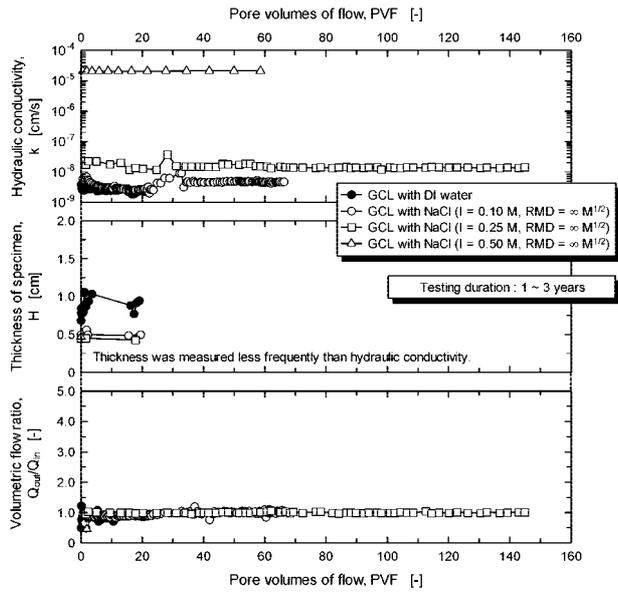


Fig. 8. The changes of the hydraulic conductivity, the thickness of specimen and the volumetric flow ratio for powdered bentonite GCL with DI water and NaCl solution

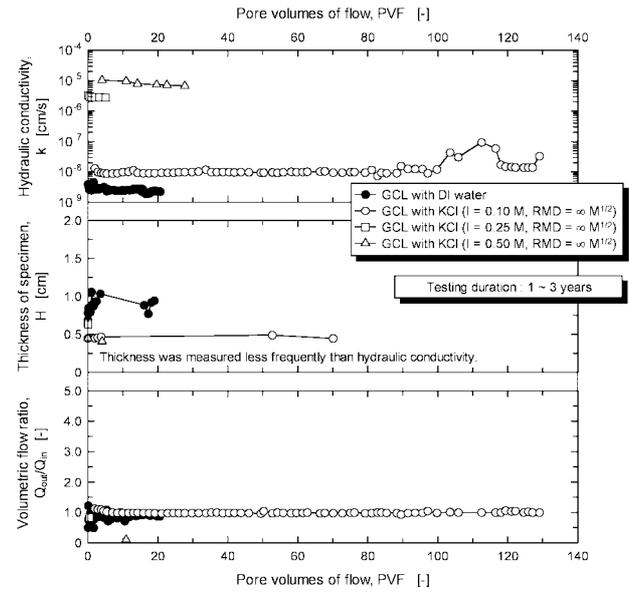


Fig. 10. The changes of the hydraulic conductivity, the thickness of specimen and the volumetric flow ratio for powdered bentonite GCL with DI water and KCl solution

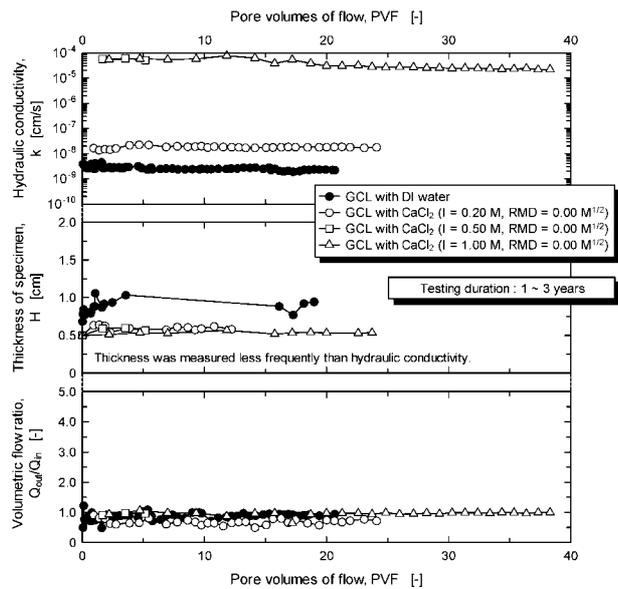


Fig. 9. The changes of the hydraulic conductivity, the thickness of specimen and the volumetric flow ratio for powdered bentonite GCL with DI water and CaCl_2 solution

conductivity value was $k = 2.1 \times 10^{-5}$ cm/s when NaCl single-species solution of $I = 0.5$ M was permeated into GCL. The electrolytic solution decreased the barrier performance of GCL. For the change in the thickness of GCL specimen, the thickness for the deionized water was increased from the initial thickness of $H = 0.5$ cm by the swelling of the bentonite contained in GCL, and was reached to approximately $H = 1.0$ cm in $\text{PVF} > 5$. This thickness was larger than that for the NaCl solution. This is because the bentonite cannot swell sufficiently for the electrolytic solution as shown in Figs. 3 and 4. The larger

swelling capacity of bentonite means that the GCL specimen became thicker and its barrier performance is superior. The deionized water could swell the bentonite, so that the GCL specimen became thick by the swelling and showed excellent barrier performance. However, when an electrolytic solution that could not swell bentonite sufficiently was permeated into the specimen, the thickness of the specimen would be almost the same as the initial value, and this specimen would show inferior barrier performance. This figure shows that the number of total plots for the thickness, H , was less than that for the hydraulic conductivity, k . This was because the thickness of the GCL specimen was not frequently measured in the testing duration. The thickness could be obtained by measuring a distance between the color filter papers, whose sides were colored with red ink; set up on the upper and the lower sides of the GCL specimen using a microscope. The thickness of the GCL specimen was frequently measured at the early stage of permeation, because the thickness changed when exposing the specimen to the permeant solution. After the early stage, little change in the thickness was observed, and the thickness was not frequently measured. The hydraulic conductivity was calculated using a latest measured thickness. The volumetric flow ratios in any of the cases were almost constant over time during the tests. Therefore, the saturation of the specimen was almost constant over time. Next, as shown in Figs. 9 and 10, the hydraulic conductivity for the single-species solution of CaCl_2 or KCl also decreased when the ionic strength of the permeant solution was strong. The hydraulic conductivity values of GCL permeated with the single-species solutions of $I = 0.5$ M were $k = 2.1 \times 10^{-5}$ cm/s (NaCl solution), $k = 5.3 \times 10^{-5}$ cm/s (CaCl_2 solution), and $k = 6.7 \times 10^{-6}$ cm/s (KCl solution), respectively.

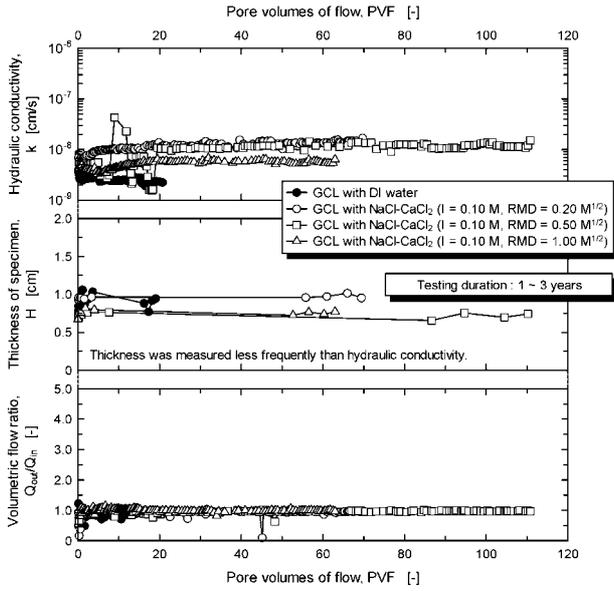


Fig. 11. The changes of the hydraulic conductivity, the thickness of specimen and the volumetric flow ratio for powdered bentonite GCL with DI water and NaCl-CaCl₂ solution of $I=0.1$ M

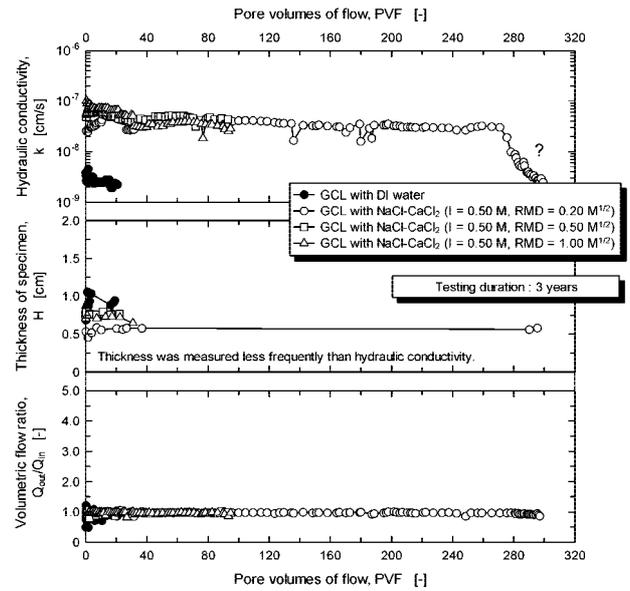


Fig. 13. The changes of the hydraulic conductivity, the thickness of specimen and the volumetric flow ratio for powdered bentonite GCL with DI water and NaCl-CaCl₂ solution of $I=0.5$ M

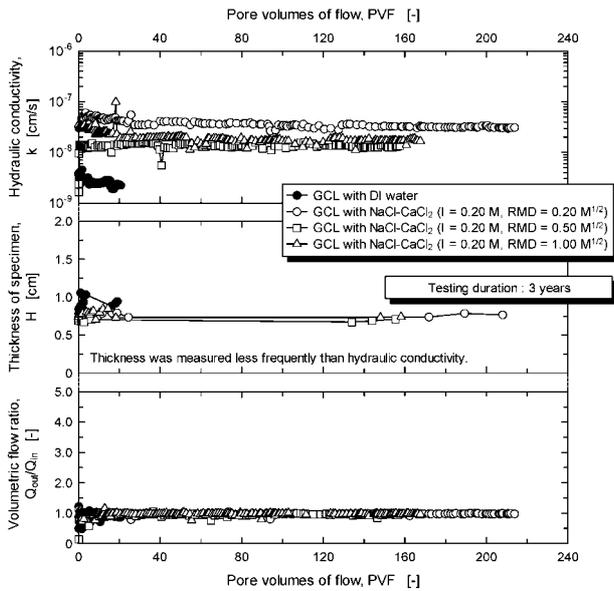


Fig. 12. The changes of the hydraulic conductivity, the thickness of specimen and the volumetric flow ratio for powdered bentonite GCL with DI water and NaCl-CaCl₂ solution of $I=0.2$ M

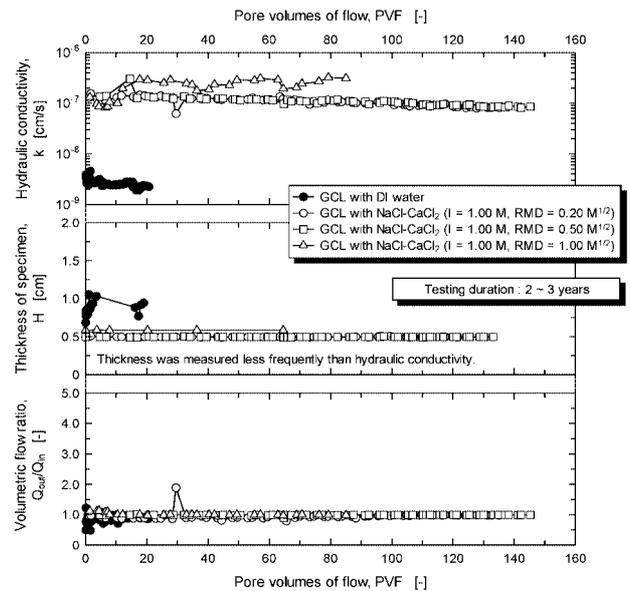


Fig. 14. The changes of the hydraulic conductivity, the thickness of specimen and the volumetric flow ratio for powdered bentonite GCL with DI water and NaCl-CaCl₂ solution of $I=1.0$ M

Figures 11 to 15 shows the results of the hydraulic conductivity test with the multi-species solutions of NaCl-CaCl₂ or NaCl-KCl. As shown in Figs. 11 to 14, the hydraulic conductivity of GCL permeated with NaCl-CaCl₂ multi-species solution having a certain ionic strength, the permeant solution having the strong ionic strength, decreased the barrier performance of GCL greatly. This reason closely relates to the above-described swelling capacity. That is, when the ionic strength of the permeant solution was stronger, the bentonite could not swell sufficiently hence the bentonite specimen showed inferior barrier performance. For the effect of the mixing ratio RMD of the NaCl solution and the CaCl₂ solution

on the hydraulic conductivity of GCL, the hydraulic conductivity value became high when a large amount of CaCl₂ was contained in the permeant solution (namely, RMD was small) under the low ionic strength as shown in Fig. 11. In general, the multivalent exchangeable cation such as calcium attracts the crystal layer, which has negative electricity, of bentonite more strongly than a monovalent exchangeable cation such as sodium, and decreases the swelling capacity of the bentonite because it becomes difficult for water molecules to enter between the crystal layers. Thus, the barrier performance is considered to deteriorate when a large amount of CaCl₂ is

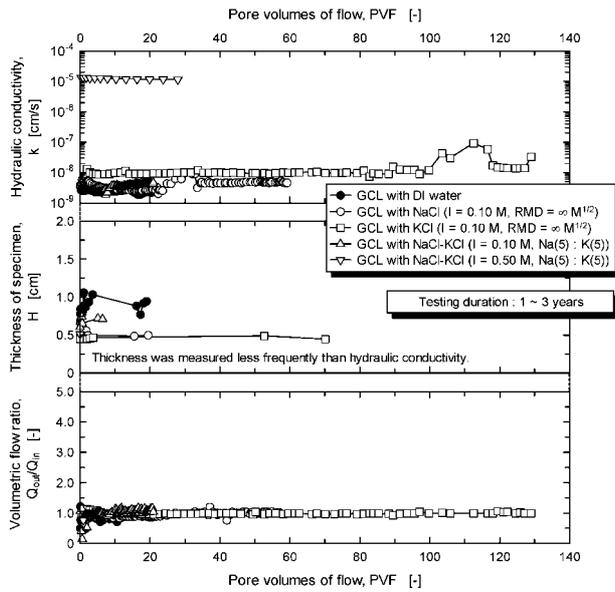


Fig. 15. The changes of the hydraulic conductivity, the thickness of specimen and the volumetric flow ratio for powdered bentonite GCL with DI water and NaCl-KCl solution

contained in the permeant solution. However, under the high ionic strength as shown in Fig. 14, the hydraulic conductivity value became small adversely when a large amount of CaCl_2 was contained in the permeant solution. In addition, from comparison of the hydraulic conductivity values for the NaCl single-species solution and the NaCl- CaCl_2 multi-species solution of $I=0.5$ M in Figs. 8 and 14, it can be stated that the hydraulic conductivity for the NaCl single-species solution is much higher than that for the NaCl- CaCl_2 multi-species solution. These findings lead to a conclusion that sodium becomes more sensitive to an increase in the hydraulic conductivity than calcium when the ionic strength increases. As the proof of this consideration, sodium decreased the free swell of bentonite more than calcium at a high ionic strength as shown in Fig. 3; the free swell values were 6.5 mL/2 g-solid for NaCl solution and 7.9 mL/2 g-solid for CaCl_2 solution at $I=0.5$ M. In part, the hydraulic conductivity value in the case of permeation with NaCl- CaCl_2 solution having $I=0.5$ M and $RMD=0.2$ $M^{1/2}$ as shown in Fig. 13 was much decreased at $PVF>280$. This is because the GCL pore might be blocked by the migration of the colloidal matters contained in GCL. On the other hand, Fig. 15 shows the hydraulic conductivity of GCL permeated with the multi-species solution of NaCl-KCl. In this figure, the hydraulic conductivity for the single-species solution of NaCl and KCl under $I=0.1$ M is shown as a reference value. When the permeant solution of $I=0.1$ M was permeated into GCL, the hydraulic conductivity for KCl solution was highest, and the hydraulic conductivity for NaCl solution was lower than that for NaCl-KCl solution. This may be due to the swelling capacity for the electrolytic solution as shown in Figs. 3 and 4; namely, it was because the KCl solution obstructed the swelling of the bentonite more seriously than NaCl solution. It was concluded that the difference

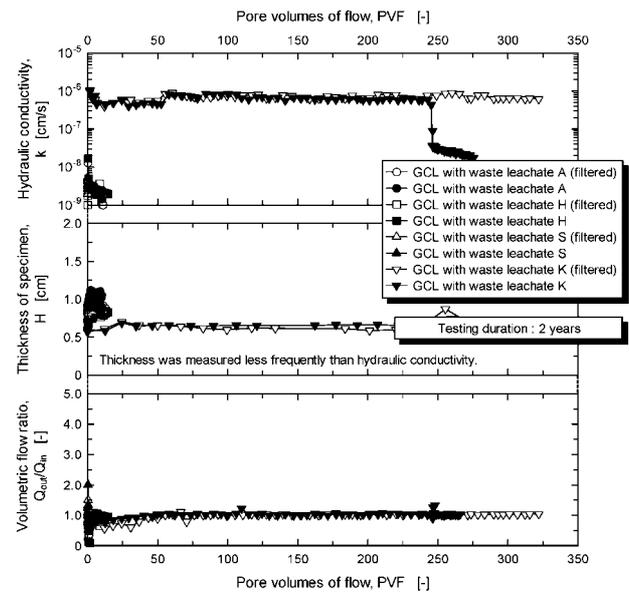


Fig. 16. The changes of the hydraulic conductivity, the thickness of specimen and the volumetric flow ratio for powdered bentonite GCL with waste leachates A, H, S, and K

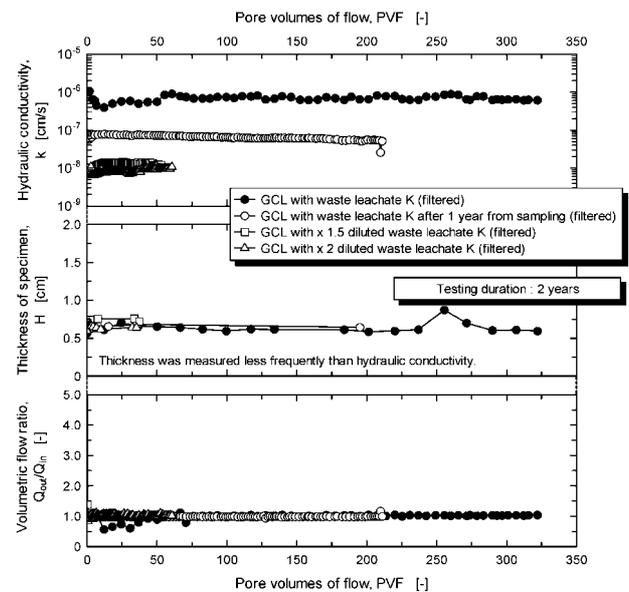


Fig. 17. The changes of the hydraulic conductivity, the thickness of specimen and the volumetric flow ratio for powdered bentonite GCL with waste leachate K and its diluted solution ($\times 1.5$ and $\times 2.0$)

in the type of cation appeared in the hydraulic conductivity value, even when the valence and concentration of cation dissolved in each solution was the same.

Figures 16 to 18 shows the results of the hydraulic conductivity test with the waste leachates. Figure 16 shows the hydraulic conductivity of GCL permeated with the waste leachates A, H, S, and K. The hydraulic conductivity values for the waste leachates A, H, and S were as low as $k < 1.0 \times 10^{-8}$ cm/s, and in contrast, the hydraulic conductivity value for waste leachate K became as high as $k = 6.4 \times 10^{-7}$ cm/s. This was because the waste leachates K had a higher concentration than any other

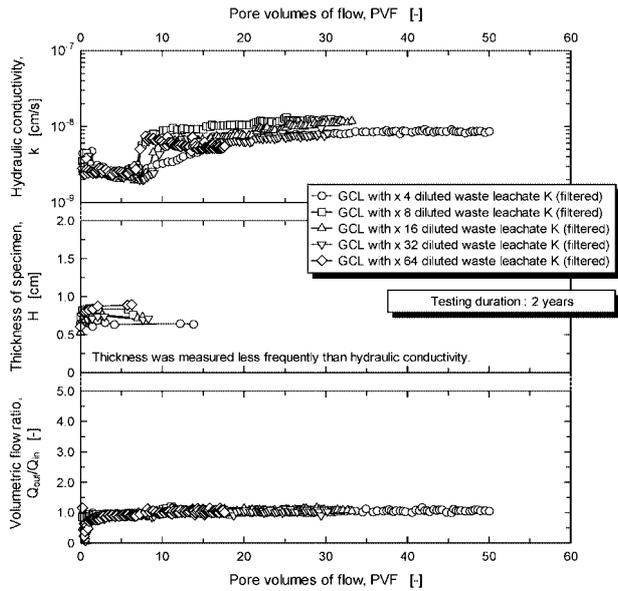


Fig. 18. The changes of the hydraulic conductivity, the thickness of specimen and the volumetric flow ratio for powdered bentonite GCL with waste leachate K and its diluted solution ($\times 4.0$ to $\times 64.0$)

leachate; the electric conductivity values were 0.24 S/m (waste leachate A), 0.93 S/m (waste leachate H), 4.17 S/m (waste leachate S), and 29.3 S/m (waste leachate K), respectively. The filtration of the waste leachates hardly affected the hydraulic conductivity value of GCL. However, the hydraulic conductivity of GCL was much decreased in $PVF=250$ as shown in the testing case to use waste leachate K without filtration. The reason for this was because the GCL pore specimen might be blocked by the colloidal matters contained in the waste leachate. Therefore, it should be noted that the barrier performance of GCL might be evaluated excessively due to clogging of the colloidal matters when the raw waste leachate was used for the test without filtration. Figures 17 and 18 show the hydraulic conductivity of GCL permeated with waste leachate K and its diluted solution. In Fig. 17, the closed circle plots indicate a testing case that was conducted immediately after sampling waste leachate K, and on the other hand, the open circle plots indicate a testing case that was conducted by using waste leachate K left alone for 1 year from its sampling. The difference of 1 order magnitude appeared in the hydraulic conductivity evaluated from each testing case. Probably, the organic substances contained may be deteriorated by leaving the waste leachate alone for 1 year. For the effects of the diluted solution on the hydraulic conductivity, the hydraulic conductivity for the diluted waste leachate was lower than that for the undiluted waste leachate. However, the difference between the dilution magnification factor of 1.5 and 2.0 hardly appeared in the hydraulic conductivity value. The testing cases of using the waste leachate diluted with more deionized water is shown in Fig. 18. This figure shows an impressive profile. When the dilution magnification factor was more than 4.0, the long-term change appeared in the hydraulic conductivity

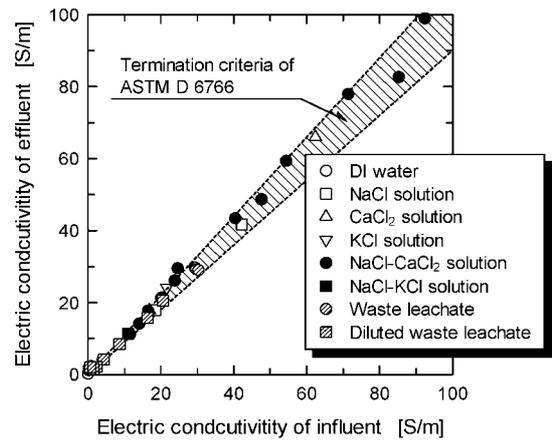


Fig. 19. Comparison in the electric conductivity of influent and effluent according to ASTM D 6766

of GCL. In any testing cases, the hydraulic conductivity of GCL was evaluated as approximately $k=2.0 \times 10^{-9}$ cm/s in $PVF=7$, but the hydraulic conductivity increased gradually over time in $PVF>7$. For the waste leachate with the dilution magnification factor of 4.0, in particular, the hydraulic conductivity increased from $k=2.0 \times 10^{-9}$ cm/s to $k=8.7 \times 10^{-9}$ cm/s very slowly in 2 years. Therefore, it was necessary to be careful for the long-term change of the barrier performance when GCL was permeated with the electric solution having a low concentration. In this study, the long-term change of the hydraulic conductivity appeared in the cases of using the waste leachates having the electric conductivity of $=8.58$ S/m, which had a value for the waste leachate with the dilution magnification factor of 4.0.

CONSIDERATIONS

Termination Criteria of Long-Term Hydraulic Conductivity Test

As a general criteria to terminate the hydraulic conductivity test, it is necessary to satisfy the following three points; (1) the hydraulic conductivity value is stable over time, (2) the volumetric flow ratio is approximately 1, and (3) the pore volumes of flow of at least 2 or more are permeated into the bentonite specimen. It is also one of the important criteria to establish the chemical equilibrium state before the test is terminated (Bowders, 1988; Shackelford et al., 1999). Shackelford et al. (1999) suggest that the electric conductivity of the influent and effluent can be used as indicators of the chemical equilibrium state, and recommend that (4) the electric conductivity ratio of the influent and effluent fall within 0.9–1.1 before the test is terminated. ASTM D 5084 explains in detail about the criteria described in the above-mentioned (1) to (3), on the other hand, ASTM D 6766 “Standard Test Method for Evaluation of Hydraulic Properties of Geosynthetic Clay Liners Permeated with Potentially Incompatible Liquids” explains the criterion regarding (4).

Most hydraulic conductivity values obtained in this study had already satisfied the criteria described in ASTM

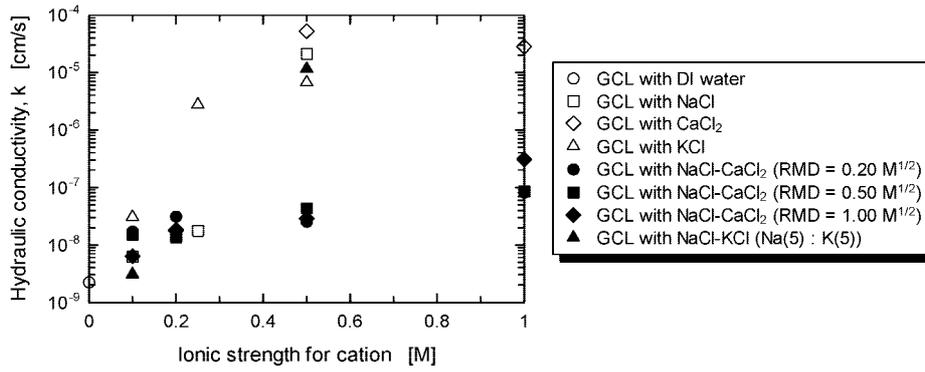


Fig. 20. Relation between the hydraulic conductivity and the ionic strength for chemical solution

Table 3. Results of long-term hydraulic conductivity test for powdered bentonite GCL

Type of solution	Permeant solution					End of testing							
	<i>I</i> [M]	<i>RMD</i> [M ^{1/2}]	Chemical compounds			pH [-]	EC [S/m]	Time [year]	<i>PVF</i> [-]	pH [-]	EC [S/m]	<i>k</i> [cm/s]	
			Na ⁺ conc. [M]	Ca ²⁺ conc. [M]	K ⁺ conc. [M]								
Deionized water	0.00	0.00	0.00	0.00	0.00	7.04	0.02	<3	20.66	8.05	0.31	2.24 × 10 ⁻⁹	
Na solution	0.10	∞	0.20	0.00	0.00	5.68	18.43	<2	59.17	8.07	18.01	4.61 × 10 ⁻⁹	
	0.25	∞	0.50	0.00	0.00	5.42	42.10	<2	144.85	7.69	41.80	1.41 × 10 ⁻⁸	
	0.50	∞	1.00	0.00	0.00	5.36	76.80	<1	58.61	—	—	2.13 × 10 ⁻⁵	
	1.00	∞	1.00	0.00	0.00	5.36	76.80	<1	58.61	—	—	2.13 × 10 ⁻⁵	
Ca solution	0.20	0.00	0.00	0.10	0.00	8.56	16.85	<1	12.22	8.19	17.81	1.83 × 10 ⁻⁸	
	0.50	0.00	0.00	0.25	0.00	8.88	35.90	<1	5.15	—	—	5.25 × 10 ⁻⁵	
	1.00	0.00	0.00	0.50	0.00	9.24	62.40	<1	23.72	6.57	66.00	2.80 × 10 ⁻⁵	
K solution	0.10	∞	0.00	0.00	0.20	7.93	21.60	<2	129.04	8.17	24.20	3.30 × 10 ⁻⁸	
	0.25	∞	0.00	0.00	0.50	7.57	49.10	<1	5.07	—	—	2.76 × 10 ⁻⁶	
	0.50	∞	0.00	0.00	1.00	7.37	95.40	<1	27.69	—	—	6.69 × 10 ⁻⁶	
Na-Ca solution	0.10	0.20	0.05	0.04	0.00	—	11.48	<3	69.69	7.16	11.31	1.70 × 10 ⁻⁸	
	0.10	0.50	0.11	0.02	0.00	—	14.01	<3	110.70	6.65	14.22	1.52 × 10 ⁻⁸	
	0.10	1.00	0.15	0.01	0.00	—	16.43	<3	62.97	6.88	17.81	6.40 × 10 ⁻⁹	
	0.20	0.20	0.08	0.08	0.00	—	20.10	<3	213.80	7.43	21.40	3.12 × 10 ⁻⁸	
	0.20	0.50	0.17	0.06	0.00	—	23.80	<3	157.58	7.51	26.20	1.37 × 10 ⁻⁸	
	0.20	1.00	0.26	0.03	0.00	—	24.60	<3	172.10	7.11	29.60	1.75 × 10 ⁻⁸	
	0.50	0.20	0.13	0.22	0.00	—	40.40	<3	296.93	8.61	43.50	2.55 × 10 ⁻⁹	
	0.50	0.50	0.30	0.18	0.00	—	47.60	<3	92.95	7.49	48.80	4.37 × 10 ⁻⁸	
	0.50	1.00	0.50	0.13	0.00	—	54.30	<3	94.74	7.04	59.40	2.86 × 10 ⁻⁸	
	1.00	0.20	0.19	0.45	0.00	—	71.30	<2	135.13	7.10	78.00	8.17 × 10 ⁻⁸	
Na-K solution	1.00	0.50	0.44	0.39	0.00	—	85.20	<2	145.29	7.29	82.70	8.63 × 10 ⁻⁸	
	1.00	1.00	0.78	0.31	0.00	—	92.40	<2	84.99	7.10	99.00	3.12 × 10 ⁻⁷	
	0.10	∞	0.10	0.00	0.10	7.59	10.95	<2	18.20	8.22	11.42	4.26 × 10 ⁻⁹	
	0.50	∞	0.50	0.00	0.50	5.98	128.80	<1	27.97	—	—	1.16 × 10 ⁻⁵	
	Waste leachate A	—	—	—	—	—	6.50	0.24	<2	10.26	7.94	1.32	1.47 × 10 ⁻⁹
	Waste leachate A (filtered)	—	—	—	—	—	6.91	0.25	<2	11.04	8.48	2.03	1.00 × 10 ⁻⁹
	Waste leachate H	—	—	—	—	—	7.97	0.93	<2	14.29	8.08	2.39	1.96 × 10 ⁻⁹
	Waste leachate H (filtered)	—	—	—	—	—	7.85	0.79	<2	14.34	7.72	2.38	1.95 × 10 ⁻⁹
	Waste leachate S	—	—	—	—	—	11.79	4.17	<2	10.87	7.72	4.27	2.17 × 10 ⁻⁹
	Waste leachate S (filtered)	—	—	—	—	—	11.74	4.08	<2	11.28	7.47	4.23	1.89 × 10 ⁻⁹
Waste leachate K	—	—	—	—	—	7.75	29.30	<2	315.59	7.03	29.80	6.38 × 10 ⁻⁷	
Waste leachate K (filtered) ¹	—	—	—	—	—	7.31	29.70	<2	322.04	7.64	29.40	6.16 × 10 ⁻⁷	
Waste leachate K (filtered) ²	—	—	—	—	—	6.40	30.30	<2	210.99	7.42	29.10	5.19 × 10 ⁻⁸	
× 1.5 diluted (filtered) ²	—	—	—	—	—	6.31	20.50	<2	52.92	7.48	20.60	1.23 × 10 ⁻⁸	
× 2 diluted (filtered) ²	—	—	—	—	—	6.25	16.26	<2	60.67	8.57	15.76	1.09 × 10 ⁻⁸	
× 4 diluted (filtered) ²	—	—	—	—	—	6.35	8.58	<2	50.01	8.07	8.53	8.66 × 10 ⁻⁹	
× 8 diluted (filtered) ²	—	—	—	—	—	6.45	4.34	<2	31.49	8.10	4.24	1.20 × 10 ⁻⁸	
× 16 diluted (filtered) ²	—	—	—	—	—	6.46	2.32	<2	33.19	8.39	2.25	1.17 × 10 ⁻⁸	
× 32 diluted (filtered) ²	—	—	—	—	—	6.39	1.46	<2	30.20	8.53	1.55	8.14 × 10 ⁻⁹	
× 64 diluted (filtered) ²	—	—	—	—	—	6.54	0.60	<2	17.62	8.24	2.13	5.50 × 10 ⁻⁹	

¹ used immediately after sampling

² used after 1 year from sampling

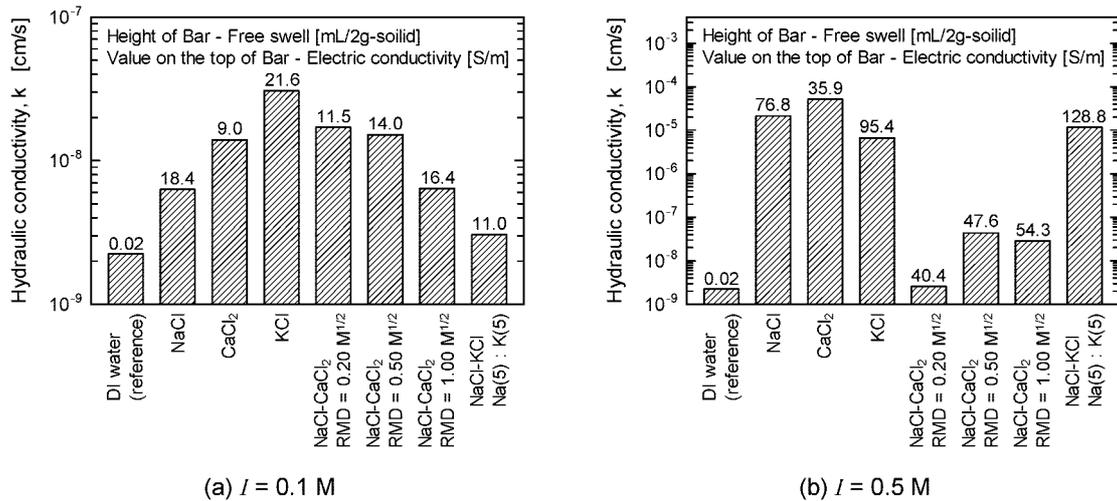


Fig. 21. Effect of the electrolytes on the hydraulic conductivity of GCL: note that the electric conductivity of each solution is quite different even if the ionic strength is the same. In actuality, the electric conductivity values of the solutions of $I=0.5$ M were 76.8 S/m (NaCl solution), 35.9 S/m (CaCl₂ solution), and 95.4 S/m (KCl solution), respectively

D 5084. However, in the cases of using the permeant solution of the low concentration, the hydraulic conductivity values increased gradually as shown in Fig. 18. The barrier performance of GCLs must be evaluated in consideration of a long-term change of the hydraulic conductivity. Figure 19 shows the electric conductivity of influent versus effluent at an ultimate state of the hydraulic conductivity test. According to ASTM D 6766 to achieve the chemical equilibrium, the hydraulic conductivity test is required to be continued until the ratio of the electric conductivity of effluent over the electric conductivity of influent falls into 0.9–1.1. Figure 19 indicates that the most hydraulic conductivity tests conducted in this research satisfy the termination criteria of ASTM D 6766. Most tested GCLs achieved a chemical equilibrium condition before the tests were terminated.

Summary of Long-Term Hydraulic Conductivity Test

The results of the long-term hydraulic conductivity test are summarized in Table 3. This table shows the properties of the permeant solution used, and the results at the end of the hydraulic conductivity test using its solution.

Figure 20 shows the relation between the hydraulic conductivity of GCL and the ionic strength of the chemical solutions. The open plots indicate the hydraulic conductivity for the deionized water or the single-species solution, and the closed plots indicate the hydraulic conductivity for the multi-species solution. The hydraulic conductivity of GCL permeated with the electrolytic solution became higher when the ionic strength of the solution was stronger. The influence on an increase in the hydraulic conductivity significantly differed between the single-species solution and the multi-species solution. Most of the hydraulic conductivity values to the multi-species solution were lower than those to the single-species solution, and these values were smaller than $k = 1.0 \times 10^{-7}$ cm/s. In part, the multi-species solution containing

only the monovalent cations of NaCl and KCl made the hydraulic conductivity as high as $k = 1.2 \times 10^{-5}$ cm/s at $I=0.5$ M. In the high ionic strength of ≥ 0.5 M, the hydraulic conductivity values to the single-species solution were approximately $k = 1.0 \times 10^{-5}$ cm/s regardless of the difference in the valence of cation. However, the multi-species solution composed of the monovalent and divalent cations increased the hydraulic conductivity values to $k = 1.0 \times 10^{-7}$ cm/s in the same range of the ionic strength. Although the hydraulic barrier of bentonite to the single-species solution has been traditionally explained from the thickness of electric diffusion double layer and the size of hydrated ionic molecule, the hydraulic conductivity to the multi-species solution cannot be simply predicted from the traditional knowledge regarding the hydraulic conductivity to the single-species solution. Figure 21 shows the effect of the electrolytes on the hydraulic conductivity of GCL under $I=0.1$ M and $I=0.5$ M. The hydraulic conductivity of GCL for CaCl₂ solution of $I=0.1$ M was referred to the data reported by Lin et al. (2000). The hydraulic conductivity for the deionized water was as low as $k = 2.2 \times 10^{-9}$ cm/s, in contrast, the hydraulic conductivity for the electrolytic solution was higher than that for the deionized water. For the hydraulic conductivity to the permeant solution of $I=0.1$ M, the KCl solution increased the hydraulic conductivity of GCL more slightly than any other solution. On the other hand, the electrolytic solutions of $I=0.5$ M showed that the hydraulic conductivity with the single-species or multi-species solution containing only monovalent cations became considerably higher than those with the multi-species solution containing divalent cation for the same ionic strength.

Next, Fig. 22 shows the hydraulic conductivity of GCL permeated with the waste leachates. As shown in Fig. 22(a), the hydraulic conductivity of GCL became higher for the waste leachate having the higher electric

conductivity. This reason can also be explained by the swelling capacity of bentonite as shown in Fig. 5. On the other hand, Fig. 22(b) shows the hydraulic conductivity for waste leachate K and its distilled solution. The hydraulic conductivity for the diluted waste leachate was lower than that for the undiluted waste leachate, and was decreased with the increase of the dilution magnification. In addition, the waste leachate that was left alone for 1 year from sampling showed the lower hydraulic conductivity than the waste leachate immediately after sampling. The organic substances contained might be deteriorated

by leaving the waste leachate alone for 1 year.

Applicability of Evaluation Methods with Chemical Inorganic Solutions

In this subsection, the results obtained by using the chemical inorganic solutions were compared with those obtained by using the real waste leachates. Here, the chemical solution means the permeant solution that was easily made of inorganic substances such as NaCl, CaCl₂, or KCl. All experimental data obtained in this study are summarized in Table 4.

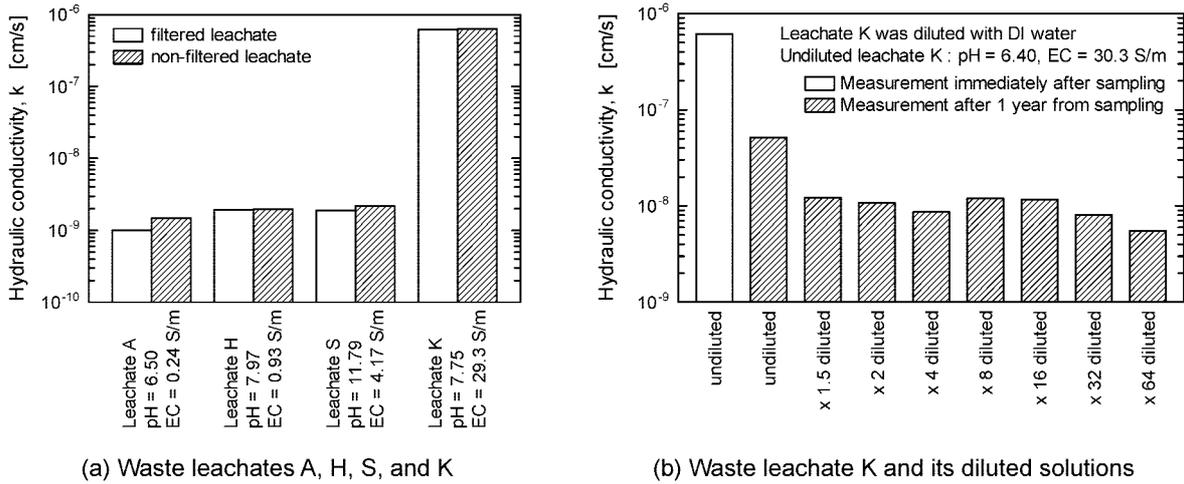


Fig. 22. Hydraulic conductivity of GCL for waste leachate

Table 4. Summary of results for powdered bentonite GCL

Type of solution	Permeant solution						Testing results				
	I [M]	RMD [$M^{1/2}$]	Chemical compounds	Na^+ conc. [M]	Ca^{2+} conc. [M]	K^+ conc. [M]	pH [-]	EC [S/m]	Free swell [mL/2 g-solid]	Liquid limit [%]	Hydraulic cond., k [cm/s]
Deionized water	0.00	0.00		0.00	0.00	0.00	7.04	0.02	33.0	619.5	2.24×10^{-9}
Na solution	0.02	∞		0.04	0.00	0.00	6.68	4.20	23.2		
	0.04	∞		0.08	0.00	0.00	6.36	8.06	19.0		
	0.05	∞		0.10	0.00	0.00	6.05	9.91	18.5		
	0.06	∞		0.12	0.00	0.00	5.72	12.09	18.0		
	0.08	∞		0.16	0.00	0.00	5.66	15.09	16.0		
	0.10	∞		0.20	0.00	0.00	5.68	18.43	15.9		4.61×10^{-9}
	0.20	∞		0.40	0.00	0.00	5.44	34.30	9.1	181.0	
	0.25	∞		0.50	0.00	0.00	5.42	42.10	8.1		1.41×10^{-8}
Ca solution	0.50	∞		1.00	0.00	0.00	5.36	76.80	6.5	111.2	2.13×10^{-5}
	1.00	∞		2.00	0.00	0.00	5.18	129.10	6.0	98.5	
	0.10	0.00		0.00	0.05	0.00	—	9.03	9.0		
	0.20	0.00		0.00	0.10	0.00	8.56	16.85	8.0	185.0	1.83×10^{-8}
	0.50	0.00		0.00	0.25	0.00	8.88	35.90	7.9	136.2	5.25×10^{-5}
K solution	1.00	0.00		0.00	0.50	0.00	9.24	62.40	7.8	114.9	2.80×10^{-5}
	0.02	∞		0.00	0.00	0.04	7.57	5.05	15.0		
	0.04	∞		0.00	0.00	0.08	7.36	9.76	11.1		
	0.05	∞		0.00	0.00	0.10	6.89	12.06	9.2		
	0.06	∞		0.00	0.00	0.12	6.81	13.55	7.2		
	0.08	∞		0.00	0.00	0.16	6.68	17.77	7.1		
	0.10	∞		0.00	0.00	0.20	7.93	21.60	7.1		3.30×10^{-8}
	0.20	∞		0.00	0.00	0.40	7.74	41.10	5.0		
	0.25	∞		0.00	0.00	0.50	7.57	49.10	5.0		2.76×10^{-6}
	0.50	∞		0.00	0.00	1.00	7.37	95.40	4.5		6.69×10^{-6}
1.00	∞		0.00	0.00	2.00	7.32	169.80	4.0			

Table 4. continued on next page...

Table 4. continued from previous page

Type of solution	Permeant solution						Testing results				
	<i>I</i> [M]	<i>RMD</i> [M ^{1/2}]	Chemical compounds			pH [-]	EC [S/m]	Free swell [mL/2 g-solid]	Liquid limit [%]	Hydraulic cond., <i>k</i> [cm/s]	
			Na ⁺ conc. [M]	Ca ²⁺ conc. [M]	K ⁺ conc. [M]						
Na-Ca solution	0.05	0.20	0.04	0.02	0.00	—	—	14.0			
	0.05	0.50	0.07	0.01	0.00	—	—	17.0			
	0.05	1.00	0.09	0.00	0.00	—	—	19.0			
	0.10	0.20	0.05	0.04	0.00	—	11.48	9.5		1.70 × 10 ⁻⁸	
	0.10	0.50	0.11	0.02	0.00	—	14.01	10.5		1.52 × 10 ⁻⁸	
	0.10	1.00	0.15	0.01	0.00	—	16.43	14.0		6.40 × 10 ⁻⁹	
	0.20	0.20	0.08	0.08	0.00	—	20.10	8.2	184.1	3.12 × 10 ⁻⁸	
	0.20	0.50	0.17	0.06	0.00	—	23.80	8.5	179.7	1.37 × 10 ⁻⁸	
	0.20	1.00	0.26	0.03	0.00	—	24.60	10.0	180.4	1.75 × 10 ⁻⁸	
	0.50	0.20	0.13	0.22	0.00	—	40.40	8.0	131.6	2.55 × 10 ⁻⁹	
	0.50	0.50	0.30	0.18	0.00	—	47.60	8.2	127.7	4.37 × 10 ⁻⁸	
	0.50	1.00	0.50	0.13	0.00	—	54.30	8.5	127.7	2.86 × 10 ⁻⁸	
	1.00	0.20	0.19	0.45	0.00	—	71.30	7.2	122.9	8.17 × 10 ⁻⁸	
1.00	0.50	0.44	0.39	0.00	—	85.20	8.0	113.6	8.63 × 10 ⁻⁸		
1.00	1.00	0.78	0.31	0.00	—	92.40	8.2	102.2	3.12 × 10 ⁻⁷		
Na-K solution	0.10	∞	0.04	0.00	0.16	7.23	11.47	11.9			
	0.10	∞	0.08	0.00	0.12	7.35	11.16	13.0			
	0.10	∞	0.10	0.00	0.10	7.59	10.95	14.0		4.26 × 10 ⁻⁹	
	0.10	∞	0.12	0.00	0.08	7.68	10.73	14.2			
	0.10	∞	0.16	0.00	0.04	7.83	10.54	16.9			
	0.50	∞	0.50	0.00	0.50	5.98	128.80	4.8		1.16 × 10 ⁻⁵	
Waste leachate A	—	—	—	—	—	6.50	0.24	28.0	580.6	1.47 × 10 ⁻⁹	
Waste leachate A (filtered)	—	—	—	—	—	6.91	0.25	28.0	629.9	1.00 × 10 ⁻⁹	
Waste leachate H	—	—	—	—	—	7.97	0.93	26.0	565.2	1.96 × 10 ⁻⁹	
Waste leachate H (filtered)	—	—	—	—	—	7.85	0.79	26.0	562.3	1.95 × 10 ⁻⁹	
Waste leachate S	—	—	—	—	—	11.79	4.17	23.0	523.5	2.17 × 10 ⁻⁹	
Waste leachate S (filtered)	—	—	—	—	—	11.74	4.08	25.0	517.7	1.89 × 10 ⁻⁹	
Waste leachate K	—	—	—	—	—	7.75	29.3	6.0	165.5	6.38 × 10 ⁻⁷	
Waste leachate K (filtered) ¹	—	—	—	—	—	7.31	29.7	5.9	165.6	6.16 × 10 ⁻⁷	
Waste leachate K (filtered) ²	—	—	—	—	—	6.40	30.30	7.0		5.19 × 10 ⁻⁸	
× 1.5 diluted (filtered) ²	—	—	—	—	—	6.31	20.50	7.1		1.23 × 10 ⁻⁸	
× 2 diluted (filtered) ²	—	—	—	—	—	6.25	16.26	8.5		1.09 × 10 ⁻⁸	
× 4 diluted (filtered) ²	—	—	—	—	—	6.35	8.58	12.1		8.66 × 10 ⁻⁹	
× 8 diluted (filtered) ²	—	—	—	—	—	6.45	4.34	17.4		1.20 × 10 ⁻⁸	
× 16 diluted (filtered) ²	—	—	—	—	—	6.46	2.32	24.7		1.17 × 10 ⁻⁸	
× 32 diluted (filtered) ²	—	—	—	—	—	6.39	1.46	27.5		8.14 × 10 ⁻⁹	
× 64 diluted (filtered) ²	—	—	—	—	—	6.54	0.60	29.5		5.50 × 10 ⁻⁹	

¹ used immediately after sampling

² used after 1 year from samplings

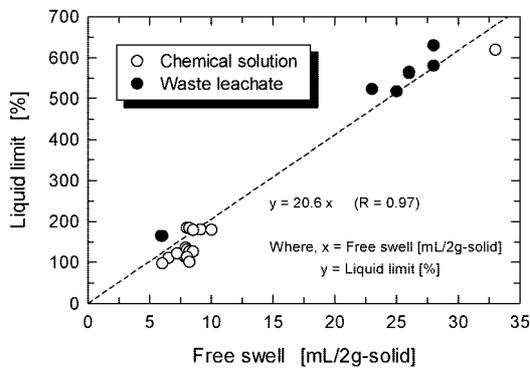


Fig. 23. Relation between the liquid limit and the free swell

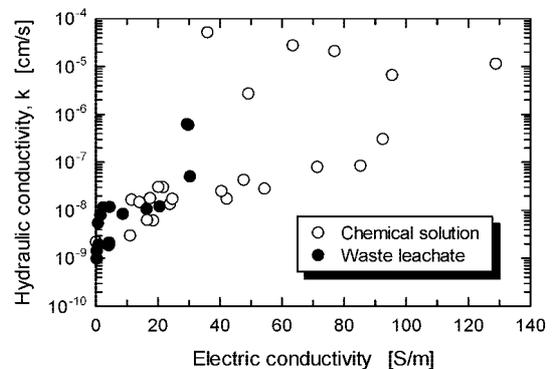


Fig. 24. Relation between the hydraulic conductivity and the electric conductivity

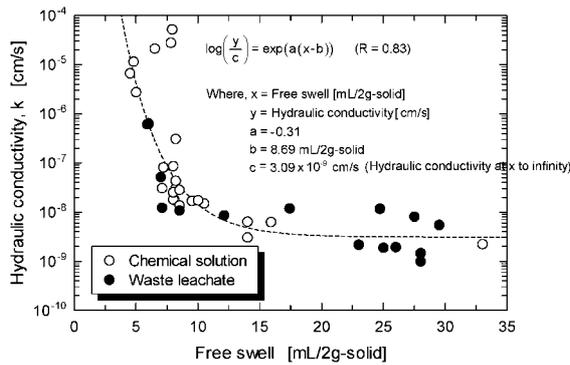


Fig. 25. Relation between the hydraulic conductivity and the free swell for GCLs confined at 29.4 kPa

Figure 23 shows the relation between the liquid limit and the free swell. The liquid limit tests were conducted on 24 types of permeant solutions as shown in Table 4. These index values were almost in a linear relation regardless of the type and concentration of the permeant solution. Figure 24 shows the relation between the hydraulic conductivity of GCL and the electric conductivity of the permeant solution. The electric conductivity was used as an indicator of the permeant solution because the ionic strength, which is widely used in permeation problems, of the waste leachate could not be calculated correctly. The tendency of the hydraulic conductivity for the chemical solution was similar to that for the waste leachate in the range of the low electric conductivity. Therefore, it was concluded that the hydraulic conductivity of GCLs to be used in landfill bottom liners can be estimated by the hydraulic conductivity values obtained from the experiment using chemical solutions having the similar electric conductivity values if the chemical solution had the electric conductivity within $= 25$ S/m. In contrast, when the chemical solution or the waste leachate has the high electric conductivity of > 25 S/m, the hydraulic conductivity value may be significantly increased and scattered. Figure 25 shows the relation between the hydraulic conductivity and the free swell. The hydraulic conductivity tests were conducted on 40 types of permeant solutions as shown in Table 4. The hydraulic conductivity of GCL could be given as a simple function of the free swell regardless of the type and concentration of the permeant solution. This relation is very useful in estimating the barrier performance of GCLs or bentonite permeated with the inorganic solution, because the barrier performance can be easily estimated by the free swell, which can be evaluated much more rapidly than the hydraulic conductivity. GCLs have excellent barrier performance of $k < 1.0 \times 10^{-8}$ cm/s when the free swell of the bentonite in GCLs is larger than 15 mL/2 g-solid.

The type and concentration of the chemical permeant solution has a significant influence on the barrier performance of GCL. However, it is too difficult to predict the type and concentration of the permeant solution before GCL is applied to a site, because the solution permeated into GCL is unspecified. Therefore, to evalu-

ate the hydraulic conductivity of GCL from the ionic strength, which is the parameter considering the type and concentration of the solution, is not practicable. In order to evaluate practicably the hydraulic conductivity of GCL, the hydraulic conductivity should be indirectly estimated from the relation between the free swell and the hydraulic conductivity as shown in Fig. 25. Even if the type and concentration of the permeant solution cannot be specified, the free swell to the solution will derive the hydraulic conductivity. This method to evaluate the hydraulic conductivity of GCL permeated with an inorganic solution is especially available in investigating the barrier performance of GCL that had been applied at a waste containment facility. The barrier performance of GCL can be estimated by (1) sampling the real waste leachate from the waste containment facility, then (2) conducting the free swell test with the waste leachate, and finally (3) evaluating the hydraulic conductivity from the obtained free swell using the regression curve:

$$\log\left(\frac{y}{c}\right) = \exp(a(x-b)) \quad (1)$$

where, x is the free swell of bentonite in GCL (mL/2 g-solid), y is the hydraulic conductivity of the GCL (cm/s), a is -0.31 , b is 8.69 mL/2 g-solid, and c is 3.09×10^{-9} cm/s which is the hydraulic conductivity at x to infinity.

CONCLUSIONS

This study investigates systematically the effects of electrolytic solutions on the barrier performance of geosynthetic clay liners (GCLs), and discusses the adequacy of the hydraulic conductivity test with the chemical solution as the prediction method of barrier performance that will be exhibited in a real site. The long-term hydraulic conductivity test was conducted on a nonprehydrated GCL permeated with the chemical inorganic solutions and the waste leachates, and showed the following results.

(1) The hydraulic conductivity of GCL significantly correlates to the swelling capacity of bentonite contained in GCL, and GCL shows excellent barrier performance of $k < 1.0 \times 10^{-8}$ cm/s when the free swell, which is an index of the swelling capacity, was larger than 15 mL/2 g-solid. (2) The effect of the electrolytic solution on the hydraulic conductivity of GCL could be explained by the ionic strength for cation contained in the solution. However, the sensitivity of the ionic strength to the hydraulic conductivity was dependent on the type of cation. Potassium had an influence on the increase in the hydraulic conductivity more than sodium, even when the valence and concentration of cation dissolved in each solution was the same. (3) The hydraulic conductivity for the multi-species solution containing the divalent cation was lower than that for the single-species or multi-species solution containing only the monovalent cation for the same ionic strength. (4) The long-term change of hydraulic conductivity appeared in the cases where waste leachates having the electric conductivity of $= 8.58$ S/m

were used. The permeant solution having the low electric conductivity intercalated a few exchangeable cations slowly into the space of crystal interlayers of clay minerals. The exchangeable sites in clay minerals were gradually occupied with the cations so that the volume of bound water was decreased with time. As a result, the permeant solution having the low electric conductivity gradually increased the hydraulic conductivity of GCLs. (5) In the range of low electric conductivity, hydraulic conductivity for the chemical solution was almost the same as that for real waste leachate having similar electric conductivity. Therefore, the hydraulic conductivity test with chemical solution, which was easily made of inorganic substances such as NaCl and CaCl₂, had a good possibility to estimate the barrier performance of GCLs that will be applied in an actual site if the chemical solution had the electric conductivity within = 25 S/m.

Improvement of the chemical compatibility of bentonite is one of the important subjects to apply GCLs to bottom liners in waste containment facilities. Application of multiswellable bentonite or prehydrated bentonite is considered an effective method of improving the chemical resistance (Onikata et al., 1996; Shackelford et al., 2000; Vasko et al., 2001; Katsumi et al., 2004; Kolstad et al., 2004b; Katsumi and Fukagawa, 2005; Lee and Shackelford, 2005a). In addition, the barrier performance of GCLs that will be applied in bottom liners is considered to be improved by the load of the wastes buried (Petrov and Rowe, 1997; Katsumi and Fukagawa, 2005). The barrier performance of modified bentonites and the effect of confined pressure acting on bentonite must be investigated in order to use GCLs securely as a barrier material in waste containment facilities.

ACKNOWLEDGMENTS

Helpful comments and discussions were provided by Professor Craig H. Benson (University of Wisconsin), Professor Masashi Kamon (Kyoto University), Dr. Masanobu Onikata (Hojun Co., Ltd.), and Mr. Mitsuji Kondo (Hojun Co., Ltd.). The GCLs were provided by Marubeni Tetsugen Co., Ltd. Thanks are due to Dr. Katsumi Mizuno (Hojun Co., Ltd.) and Dr. Kazuto Endo (NIES) for providing the waste leachates for the study. Assistance with the experimental work was provided by former students of Ritsumeikan University including Shinya Hasegawa, Shugo Numata, and Masato Yokoi.

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