

EVALUATING METHODS TO MODIFY THE CHEMICAL RESISTANCE OF GEOSYNTHETIC CLAY LINERS

T. Katsumi¹, H. Ishimori², and R. Fukagawa³

ABSTRACT: In order to reduce the barrier performance deterioration in bottom clay liners at waste containment facilities, this study investigated the effectiveness of (1) using manufactured modified bentonites, (2) prehydrating natural bentonites, and (3) confining natural bentonites at high effective pressure based on the hydraulic conductivity tests. The results showed that a modified bentonite of “multi-swellable bentonite” exhibited a low hydraulic conductivity of $< 1.0 \times 10^{-8}$ cm/s for NaCl solutions with molar concentration of ≤ 1.0 M, and a manufactured modified geosynthetic clay liner (GCL) of “dense-prehydrated GCL” exhibited an extremely low hydraulic conductivity of $< 1.0 \times 10^{-10}$ cm/s for any CaCl_2 solutions tested. Prehydrated bentonite, which is naturally prehydrated by absorbing the moisture in the underlying base layer, also exhibited a low hydraulic conductivity of $< 1.0 \times 10^{-8}$ cm/s for the permeation of any CaCl_2 solutions tested. Although the permeant solutions with high concentration and ionic valence increased the hydraulic conductivity of natural bentonite, higher confining pressures decreased the void ratio of the bentonite even for the chemical solutions so that the confined bentonite could exhibit a low hydraulic conductivity of $< 1.0 \times 10^{-9}$ cm/s even to the NaCl solutions and CaCl_2 solutions.

KEYWORDS: bentonite, chemical compatibility confining pressure, hydraulic conductivity, prehydration

INTRODUCTION

Clay liners used as bottom liners in waste containment facilities are required to have low hydraulic conductivities to prevent contamination of groundwater. Geosynthetic clay liners (GCLs) are factory-manufactured clay liners that consist of a thin layer of bentonite clay encased by geotextiles or glued to a geomembrane. GCLs have been considered as alternatives to current hydraulic barrier materials or as materials that can be combined with a compacted clay layer because they are cost effective, easy to install, and exhibit low hydraulic conductivity to water.

The low hydraulic conductivity of GCLs is due to the swelling of the bentonite, but bentonite has insufficient swelling against electrolytic solutions such as leachates from waste containment facilities. The barrier performance of GCLs directly exposed to leachates at waste containment facilities may deteriorate because the bentonite in GCLs has insufficient swelling against electrolytic chemical solutions. It has been reported that hydraulic conductivity values increased as the concentration of the electrolytic solution increased (Ruhl and Daniel 1997; Jo et al. 2001; Katsumi et al. 2007).

Because deterioration is due to such chemical attacks, many researchers have developed and proposed methods to improve the chemical resistance of GCLs. These methods include (1) to use chemically-resistant bentonites (Katsumi et al. 2004, 2007b; Kolstad et al. 2004; Onikata et al. 1996; Gates et al. 2004; Lo and Yang 2001), (2) to hydrate bentonites before prior to chemical solutions (Daniel et al. 1993; Lee and Shackelford 2005; Vasko et al. 2001), and (3) to confine bentonites with a higher effective stress (Katsumi and Fukagawa 2005; Petrov and Rowe 1997).

There are still few reports that the chemical compatibility and the hydraulic conductivity of (1) manufactured modified bentonites, (2) prehydrated natural bentonites, and (3) confined natural bentonites at high effective pressure were systematically investigated. This study focused on the effects of the electrolytic chemical solutions on the long-term barrier performance of these modified bentonites, which mean chemically-resistant bentonite, prehydrated natural bentonite, or confined natural bentonite. This paper systematically showed the results of the hydraulic conductivity tests using NaCl or CaCl_2 solutions, and discussed the effectiveness of these modified bentonites.

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EXPERIMENTAL CONDITIONS

Materials

To evaluate the barrier performance against chemical attack, three types of materials were used: (a) natural bentonite (NB), (b) multiswellable bentonite (MSB), (c) geosynthetic clay liner (GCL), and (d) dense prehydrated geosynthetic clay liner (DPH-GCL). NB and MSB used in this study were obtained from the same source, and MSB was produced mixed with propylene carbonate to activate the osmotic swelling. These bentonites are available in granular form. GCL was a GCL where powdered sodium bentonite is encapsulated between a polypropylene woven geotextile and a polypropylene nonwoven geotextile by needlepunching fibers. DPH-GCL contains a prehydrated powdered bentonite that is encapsulated between a polypropylene woven geotextile and a polypropylene nonwoven geotextile. Water content and particle density for each bentonite material are: (a) 7.62% and 2.65 g/cm³ for NB, (b) 9.38% and 2.48 g/cm³ for MSB, (c) 10.00% and 2.84 g/cm³ for the bentonite in GCL, and (d) 62.47% and 2.73 g/cm³ for the bentonite in DPH-GCL, respectively.

Hydraulic Conductivity Test

For NB, MSB, GCL and DPH-GCL

The hydraulic conductivity tests were conducted according to ASTM D 5084. The tests were performed using flexible-wall permeameters with a cell pressure of 20–30 kPa and an average hydraulic gradient of 80–90.

The procedure was as follows. In order to prepare the specimen for the test, GCL and DPH-GCL were cut so that it had a 6 cm diameter. For the tests involving NB and MSB, the granular bentonite was loosely packed in a mold that had a 6 cm diameter and was 1 cm high. Then this molded specimen was sandwiched between two color filter papers attached with the woven geotextiles, and placed on the pedestals. The sides of this specimen were restrained with a rubber membrane. The membrane received a hydraulic pressure of 20–30 kPa by filling the outside cell with water, so that the solution could uniformly permeate through the specimen without leaking from the space between the side of the specimen and the rubber membrane. For specimens permeated with chemical solutions, the solutions were directly permeated from the influent point.

The flow volumes, the thicknesses and the hydraulic conductivity values of the specimen were measured over the testing duration. The thickness could be obtained by measuring a distance between the color filter papers, which side was colored with red ink, set up on the upper

and the lower sides of the GCL specimen using a cathetometer. The hydraulic conductivity was calculated using a latest measured thickness. The hydraulic conductivity tests were continuously performed to check the change in the hydraulic conductivity with time. The representative value of the hydraulic conductivity to a solution was determined by considering the chemical equilibrium before the test was terminated, according to ASTM D 6766 "Standard Test Method for Evaluation of Hydraulic Properties of Geosynthetic Clay Liners Permeated with Potentially Incompatible Liquids".

For prehydrated GCL

Prehydrated GCL was prepared using the apparatus as shown in Fig. 1. Toyoura sand was compacted at an optimum water content of 15% using a compaction test mold, which measured 10 cm in diameter, 12.7 cm in height, and 1,000 cm³ in volume. The compacted soil was removed to an acrylic mold, which had a 10 cm diameter and 15 cm height, and was used as the base layer in the prehydration test. Next, a GCL was trimmed to a 10 cm diameter and then it was placed on the base layer with a confining pressure of 5 kPa. The acrylic mold with the base layer was placed in a water tank, which size is a 60 cm width×30 cm depth×35 cm height, with a water level of 1 cm as water supply source, and the tank was closed. Then this tank was placed in a constant temperature room controlled at 20 °C, and the GCL was cured for 7–31 days.

The GCL prehydrated in this prehydration test was cut into a diameter of 6 cm as the specimen for the hydraulic conductivity test. Here, the average of the water content of the specimen was indirectly estimated from the water content values of the remaining bentonite pieces after the trimming. The hydraulic conductivity of the prepared specimen was evaluated based on ASTM D 5084. Testing condition was the same as that in the hydraulic conductivity test with MSB and DPH-GCL.

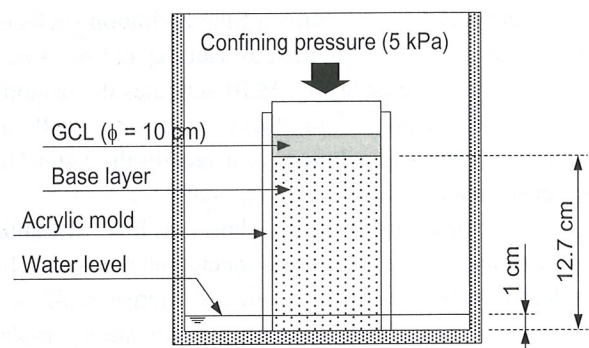


Fig. 1 Apparatus to prehydrate a GCL

For consolidated NB

To investigate the relationship between the void ratio and the hydraulic conductivity of the consolidated NB permeated with electrolytic chemical solutions, the consolidation of NB and the permeation of the solutions were conducted in fixed-ringed permeameters.

The procedure was as follows. The granular NB was loosely put in a fixed-ringed permeameter so that the thickness may become 1 cm, and then was hydrated with a permeant chemical solution. The NB was consolidated with a confining pressure for 24 hours. If the degree of the consolidation was more than 90%, the consolidated NB was permeated with the permeant solution with the same confining pressure and a hydraulic gradient of 80–90. The hydraulic conductivity test was continued until the termination criteria shown in ASTM D 5084 and D 6766 were satisfied. The void ratio and the hydraulic conductivity were calculated from the final thickness, which was measured by displacement gauge.

RESULTS

Manufactured Modified Bentonites

The hydraulic conductivities of two manufactured modified bentonites, MSB and DPH-GCL, are shown in Figs. 2 and 3. The hydraulic conductivities of NB and GCL were showed as reference values in these figures. The hydraulic conductivity of NB gradually increases for a NaCl solution with a stronger molar concentration. In contrast, MSB maintains a low hydraulic conductivity value of $k < 1.0 \times 10^{-9}$ cm/s up to a molar concentration of 1.0 M. However, when the molar concentration of the NaCl solution is 2.0 M, the hydraulic conductivity of MSB is nearly identical to that of NB. The MSB material's swelling is formed by propylene carbonate (PC) which is included in the MSB. PC can easily form a hydration shell by forming intermolecular hydrogen bonds between the outer limits of the hydration shells of the exchange cations. PC thereby can expand the space between adjacent clay layers. MSB activates the osmotic swelling of bentonite in fresh water as well as electrolytic chemical solutions, whereas in the latter NB cannot sufficiently swell.

The nonprehydrated GCL shows a low hydraulic conductivity for the deionized water, but the hydraulic conductivity of the GCL drastically increases for the permeation of a CaCl_2 solution with a strong molar concentration. The value becomes $k > 1.0 \times 10^{-5}$ cm/s when the molar concentration of the CaCl_2 solution exceeds 0.2 M. In contrast, prehydrated DPH-GCL displays extremely low hydraulic conductivity values (k

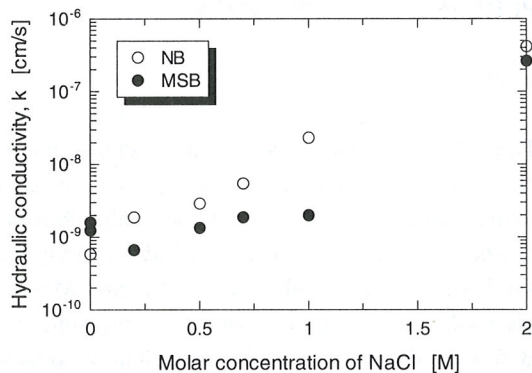


Fig. 2 Hydraulic conductivity of NB and MSB (Katsumi et al. 2007b)

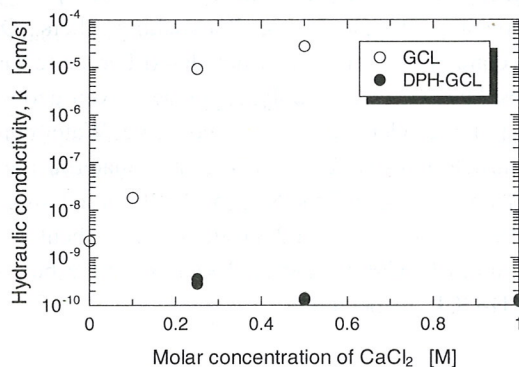


Fig. 3 Hydraulic conductivity of GCL and DPH-GCL (Katsumi et al. 2007b)

$\approx 1.0 \times 10^{-10}$ cm/s) for the CaCl_2 solutions, regardless of the tested CaCl_2 concentration level. The reason that DPH-GCL can exhibit an extremely low hydraulic conductivity is related to the prehydration effect and the consolidation effect of bentonite. It has been previously reported that prehydrated bentonite prevents a decreased barrier performance and void ratio upon exposure to chemical solutions. In addition, the effective pore space (the mobile water phase), which can pass permeant liquids, in the prehydrated bentonite is narrowed by the consolidation of a DPH-GCL in the manufacturing process. The consolidation of bentonite can increase the solid phase and immobile water phase relative to the mobile water phase so that the consolidated bentonite can obstruct the flow.

Prehydrated GCL

When GCLs are applied to bottom liners at waste containment facilities, they are naturally prehydrated because the bentonites in them absorb moisture in the underlying base layer on which they are installed. Fig. 4 shows the water content and the hydraulic conductivity of the GCLs prehydrated on the base layer as shown in

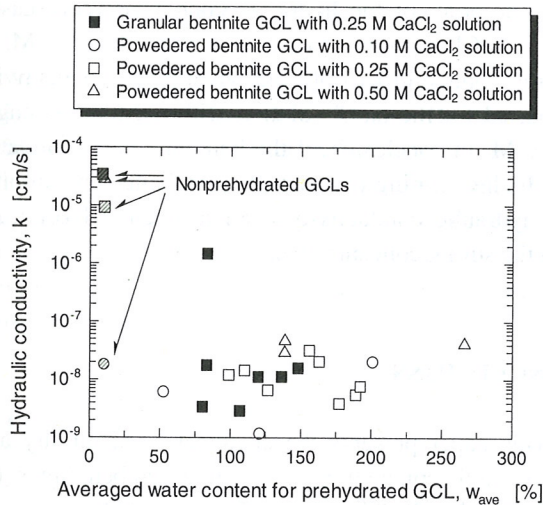


Fig. 4 Relationship between the hydraulic conductivity and the prehydration water content

Fig. 3, which simulates a prehydration process where an installed GCL at a real site was hydrated by absorbing moisture from base layer soil.

Fig. 4 shows the relationship between the hydraulic conductivity and the prehydration water content. Most of the prehydrated GCLs could exhibit the low hydraulic conductivity of $k \approx 1.0 \times 10^{-8}$ cm/s to any CaCl_2 solutions when the prehydration water content of GCL was more than 50%. However, one of the GCLs with granular bentonite exhibited the higher hydraulic conductivity of $k = 1.5 \times 10^{-6}$ cm/s than others. It may be because the granular bentonite makes it difficult to homogeneously prehydrate GCLs. Even when one bentonite granular gets wet, it may not be easy for the pore water in the granular to freely disperse to another neighboring granular beyond the space between these granules. Even if the other parts are sufficiently hydrated and swelled with a high water content, the permeation of permeant liquids concentrates on the parts insufficiently swelled, which have a low water content, so that the hydraulic conductivity of the entire GCL becomes high. Therefore, the granular bentonite makes it difficult to be homogeneously prehydrated, and the hydraulic conductivity of prehydrated GCLs with the granular bentonite is easily dispersed. It will be so difficult to estimate the barrier performance of prehydrated GCLs with the granular bentonite.

The difference between nonprehydrated GCLs and prehydrated GCLs was considered as follows. The prehydration treatment maintains an extremely low hydraulic conductivity even to the permeation of the aggressive chemical solutions such as CaCl_2 solutions. In particular, the effect of the prehydration treatment greatly appears in the hydraulic conductivity when the CaCl_2 solution with a high concentration permeates into

the GCL. The swelling capacity of the nonprehydrated GCL is seriously decreased by the permeation of a CaCl_2 solution with a molar concentration of 0.5 M so that the hydraulic conductivity increases up to $k = 2.8 \times 10^{-5}$ cm/s. In contrast, if the GCL is prehydrated before exposing to the solution, the prehydrated GCL maintains a low hydraulic conductivity of $k \approx 1.0 \times 10^{-8}$ cm/s. Thus, it is concluded that prehydration effectively improves the chemical resistance of GCLs. The powdered bentonite more reliably improves the chemical resistance. It is difficult to definitely improve the chemical resistance of GCLs with granular bentonite by prehydration.

Consolidated NB

GCLs which are applied as bottom liners are confined by the load of the wastes buried. The bentonite in the GCLs is consolidated, and the void ratio is decreased. The consolidation of bentonite can increase the solid phase and immobile water phase relative to the mobile water phase, which means the effective pore space decreased, so that the consolidated bentonite can obstruct the flow even to electrolytic chemical solutions. The load of the wastes is one of the factors that affect the barrier performance of GCLs at real sites.

Figs. 5 and 6 show the relationship between hydraulic conductivity, the confining pressure and the void ratio. In these figure, the concentration of the permeant solution is arranged by the ionic strength, I :

$$I = \frac{1}{2} \sum c_i z_i^2 \quad (1)$$

where c_i and z_i are the concentration and the valence of the i -th ion. The ionic strength is calculated from the concentration of the cations contained in the permeant solution because the cations are significantly dependent on the free swell and the hydraulic conductivity of bentonites.

The hydraulic conductivity of bentonite is decreased with the confining pressure. In a low confining pressure, the hydraulic conductivity is strongly dependent on the ionic strength of the permeant solution. The solution with the strong ionic strength and the high ionic valence seriously increases the hydraulic conductivity due to insufficient swelling of the bentonite. In contrast, the hydraulic conductivities of the bentonites which were confined at the high effective pressure of 316 kPa were about $k \approx 1.0 \times 10^{-9}$ cm/s regardless of the type of the permeant solutions. It is because the solid phase and immobile water phase are relatively increased by the consolidation. Thus, the effective pore space which affects the mobility of the permeant liquid is narrowed.

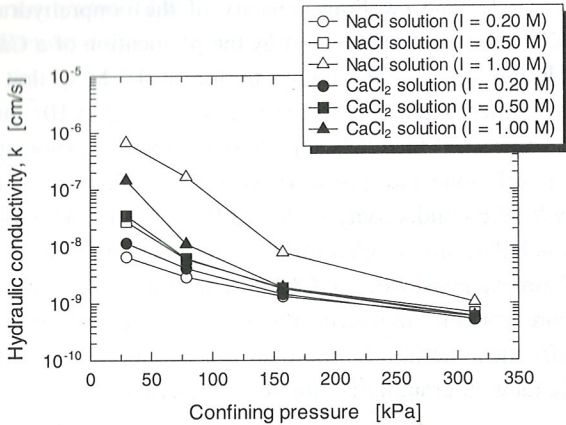


Fig. 5 Relationship between the hydraulic conductivity and the confining pressure

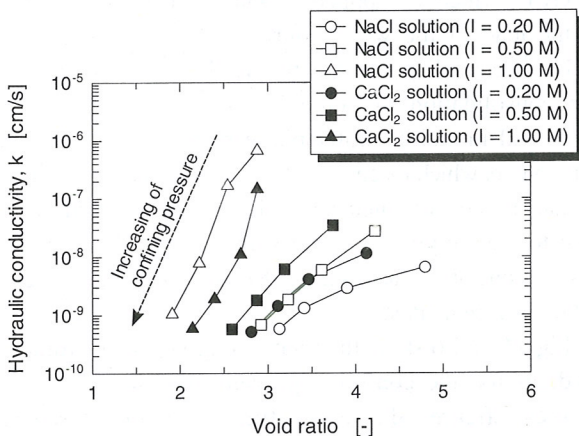


Fig. 6 Relationship between the hydraulic conductivity and the void ratio

Waste leachate is collected in the deepest parts of waste containment facilities. Although the possibility of the leakage of the waste leachate is considered high, GCLs which are installed in such parts are consolidated by the large load and expected to exhibit a low hydraulic conductivity.

The relationship between the hydraulic conductivity and the void ratio as shown in Fig. 6 is discussed. The relationship is strongly dependent on the concentration of the permeant solution. In the low concentration level, the bentonite can be sufficiently swelling so that the void ratio is large and the hydraulic conductivity is low. The permeant solution with the high concentration, however, decreases the swelling capacity of the bentonite. Thus, the bentonite permeated with the solution having the high concentration level shows the low void ratio and the high hydraulic conductivity at a low confining pressure. When the confining pressure is increased from 29.4 kPa to 314 kPa, the hydraulic conductivity is decreased with the void ratio. The degree of this change, in particular, is remarkable in the high concentration level. For example,

only one-order of the hydraulic conductivity decreased for the NaCl solution with the ionic strength of 0.2 M. In contrast, three-order of the hydraulic conductivity decreased for the NaCl solution with the ionic strength of 1.0 M. In conclusion, if the bentonite is consolidated by a high confining pressure, the bentonite can exhibit a low hydraulic conductivity even to chemical solutions with the strong concentration.

CONCLUSIONS

This paper presents the chemical compatibility and the hydraulic conductivity of (1) modified bentonites, (2) prehydrated GCL, and (3) confined natural bentonites at high effective pressure.

The hydraulic conductivity of a multi-swelling bentonite (MSB) is lower than that of natural bentonite (NB) for the permeation of a NaCl solution. MSB exhibits a good chemical resistance for NaCl solutions with a molar concentration of ≤ 1.0 M. The hydraulic conductivity of a dense prehydrated geosynthetic clay liner (DPH-GCL) is as low as $k = 1.0 \times 10^{-10}$ cm/s for CaCl₂ solutions with a molar concentration of ≤ 1.0 M. DPH-GCL also exhibits a more remarkable chemical resistance than ordinary geosynthetic clay liner (GCL).

Most of the prehydrated GCLs exhibit a low hydraulic conductivity of $k \approx 1.0 \times 10^{-8}$ cm/s against CaCl₂ solutions with concentrations between 0.1 and 0.5 M, when the prehydration water content of the GCLs are more than 50%. The prehydrated GCL exhibits a much lower hydraulic conductivity than the nonprehydrated GCL. The prehydration treatment gives GCLs an extremely low hydraulic conductivity even to the permeation of the aggressive chemical solutions such as CaCl₂ solutions.

The hydraulic conductivity of bentonite is decreased with the increase in confining pressure. In a low confining pressure, the hydraulic conductivity is strongly dependent on type of chemicals and the ionic strength of the permeant solution. In contrast, the hydraulic conductivities of the bentonites which were confined at the high effective pressure of 316 kPa were about $k \approx 1.0 \times 10^{-9}$ cm/s regardless of the type of the permeant solutions. Although bentonites do not have a capability of exhibiting a good barrier performance to chemical solutions with the high concentration level, the high confining stress may provide the narrow effective pore spaces which provide the free mobility of the permeants, and then the barrier performance may be improved. If the bentonite is consolidated by a high confining pressure, the bentonite can exhibit a low hydraulic conductivity even to chemical solutions with the strong concentration.

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