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Long-term hydraulic conductivity of modified GCL permeated with inorganic chemical solutions

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ABSTRACT: This paper presents long-term hydraulic conductivity test results on modified geosynthetic clay liner (GCL) materials permeated with inorganic chemical solutions and discusses their chemical compatibility and applicability to waste containment facilities. Two types of modified materials are used: (1) multiswellable bentonite (MSB), which has improved chemical resistance since the bentonite is treated with propylene carbonate, and (2) dense prehydrated GCL (DPH-GCL). To investigate the chemical compatibility of these two modified materials, hydraulic conductivity tests with a single-species solution of NaCl or $CaCl_2$ were conducted for 3-5 years. The hydraulic conductivities of MSB with a NaCl solution, which had a molar concentration of $\leq$ 1.0 M, were approximately k = 1.0 x 10^{-9} cm/s. The chemical compatibility of MSB was high compared to the hydraulic conductivities of natural bentonite (NB). The hydraulic conductivities of DPH-GCL with a $CaCl_2$ solution, which had a molar concentration of $\leq$ 2.0 M, were approximately k = 1.0 x 10^{-10} cm/s regardless of the concentration of the solution tested.

1 INTRODUCTION

To prevent contamination of groundwater, clay liners used as bottom liners in waste containment facilities must have low hydraulic conductivities. 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, require small space, and exhibit low hydraulic conductivity to water. The low hydraulic conductivity of GCLs is due to the swelling of the bentonite. However, bentonite has insufficient swelling against electrolytic solutions such as leachates from waste containment facilities. Thus, the barrier performance of GCLs may deteriorate when GCLs are directly subjected to waste leachates. Hence, numerous studies have examined the chemical compatibility of bentonites and GCLs, and have shown that the type and concentration of chemicals affect the hydraulic conductivity. It has been reported that the hydraulic conductivity value increases as the concentration of the electrolytic solution increases (Ruhl and Daniel 1997; Petrov and Rowe 1997; Shackelford et al. 2000; Jo et al. 2001, Katsumi et al. 2004).

Therefore, the development of modified bentonite may improve the chemical resistance. Onikata et al. (1996) discovered that propylene carbonate (PC) can be utilized as a swelling activation material to natural bentonite (NB). NB-PC complex, which is called “multiswellable bentonite (MSB)”, exhibits sufficient swelling against electrolytic solutions and fresh water (Onikata et al. 1996; Shackelford et al. 2000, Katsumi et al. 2004, Katsumi and Fukagawa 2005).

Hydrating the bentonite before exposing to electrolytic solutions is also an effective method to enhance the chemical resistance (Shan and Daniel 1991; Ruhl and Daniel 1997; Vasko et al. 2001). Dense prehydrated GCLs (DPH-GCLs) consist of a factory prehydrated natural bentonite central core and one/two geotextile layers. Kolstad et al. (2004) investigated the hydraulic conductivity of DPH-GCLs for three permeant solutions: deionized water, NaCl solution, and $CaCl_2$ solution. Both the NaCl and $CaCl_2$ solutions had a concentration of 1.0 M. They showed that the hydraulic conductivity values to the three solutions were lower than 1.0 x 10^{-10} cm/s.

In this study, the hydraulic conductivity tests were conducted on three bentonite materials (NB, MSB, and DPH-GCL) for 3-5 years to investigate whether MSB and DPH-GCL have better chemical resistance and long-term stability than NB.

2 EXPERIMENTAL METHODS

2.1 *Materials used*

To evaluate the barrier performance against chemical attack, three types of materials were used: (1) natural bentonite (NB), (2) multiswellable bentonite (MSB), and (3) dense prehydrated geosynthetic clay liner (DPH-GCL). NB and MSB used in this study were obtained from Hojun Co., Ltd. These bentonites are available in granular and powdered forms. DPH-GCL, which was purchased from Rawell Environmental Ltd., contains a prehydrated powdered bentonite that is encapsulated between a polypropylene woven geotextile and a polypropylene nonwoven geotextile. The initial thickness was about 5.0 mm. The natural water content and the particle density were (1) 7.62% and 2.65 g/cm^3 for NB, (2) 9.38% and 2.48 g/cm^3 for MSB, and (3) 62.47% and 2.73 g/cm^3 for the bentonite contained in DPH-GCL, respectively.

2.2 *Permeant solutions*

The chemical substances used for the permeant liquids were NaCl and $CaCl_2$. The permeant solutions were made by parametrically changing the ionic strength, I, and the ratio of monovalent to divalent, *RMD*. The ionic strength, I, is calculated as

$$I = \frac{1}{2}\sum c_i z_i^2 \tag{1}$$

where c_i and z_i are the concentration and the valence of the i-th ion, respectively. 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 ratio of monovalent to divalent, *RMD*, is calculated as

$$RMD = \frac{c_M}{\sqrt{2c_D}} \tag{2}$$

where c_M and c_D are the concentration of monovalent and divalent cations, respectively.

2.3 *Free swell and liquid limit test*

Free swell tests were performed according to ASTM D 5890. The bentonites used in this test were the powdered forms of NB and MSB.

The liquid limit tests were performed according to JIS A 1205. The bentonites used in this test were the powdered forms of NB and MSB, and the prehydrated powdered bentonite obtained from DPH-GCL. The bentonite soaked solution was covered with lapping so that the moisture in the sample could not evaporate during this test.

2.4 *Hydraulic conductivity test*

Granular forms of NB and MSB, and DPH-GCL were used for the hydraulic conductivity tests. 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, DPH-GCL was 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 filter papers attached with the woven geotextiles, and placed on the pedestals. The sides of this specimen were restrained with a rubber membrane. This 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 without prehydration. The tests were performed for less than 6 years. The flow volumes, thickness, and hydraulic conductivity of the specimen were measured during that time.

3 RESULTS AND CONSIDERATIONS

3.1 *Free swell*

Figure 1 shows the free swells of NB and MSB with NaCl solutions and $CaCl_2$ solutions. The open plots show the results for NB and the hatched plots show the results for MSB. The free swells of NB and MSB became smaller for electrolytic solutions at higher concentrations. When the ionic strengths were equivalent, the free swell for the $CaCl_2$ solution is smaller than that for the NaCl solution.

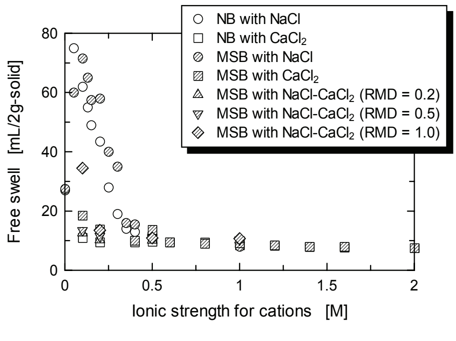

Figure 1. Relationship between the free swell and the ionic strength of the permeant solution

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3.2 *Liquid limit*

Figure 2 shows the liquid limits of NB, MSB, and the prehydrated powdered bentonite contained in DPH-GCL with NaCl solutions and $CaCl_2$ solutions. The closed plots show the results for the prehydrated powdered bentonite contained in DPH-GCL. The liquid limits of NB, MSB, and DPH-GCL became smaller for electrolytic solutions at higher concentrations. MSB has the highest liquid limit for the materials test, which implies that MSB can absorb more moisture, even if the moisture includes electrolytes. The hydraulic barrier performance of MSB may be superior for electrolytic solutions because MSB can make a large immobile water phase. In contrast, DPH-GCL has the lowest liquid limit of the tested materials.

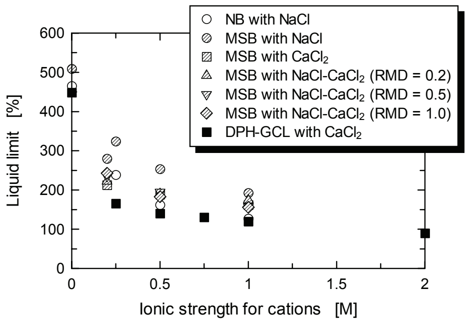

Figure 2. Relationship between the liquid limit and the ionic strength of the permeant solution

3.3 *Hydraulic conductivity*

Figures 3 to 5 show the results of the long-term hydraulic conductivity tests using NB, MSB, and DPH-GCL, respectively. Figure 3 indicates that the hydraulic conductivity of NB with DI water is very low: $k = 1.0 \times 10^{-9}$ cm/s. However, the permeation of a NaCl solution with a higher concentration increased the hydraulic conductivity. In contrast, the hydraulic conductivities of MSB are approximately $k = 1.0 \times 10^{-9}$ cm/s for a NaCl solution with any concentration level, except with an ionic strength of 1.0 M (see Figure 4). Thus, it is demonstrated that the barrier performance of MSB is superior to that of NB in the range of $I \leq 0.5$ M.

Figure 5 indicates that regardless of the $CaCl_2$ concentration, the hydraulic conductivity of DPH-GCL is $k = 1.0 \times 10^{-10}$ cm/s. Although these tests have been conducted for 3 years, sufficient pore volumes of flow have yet to be obtained. Hence, these tests will be continued in order to investigate long-term barrier performances.

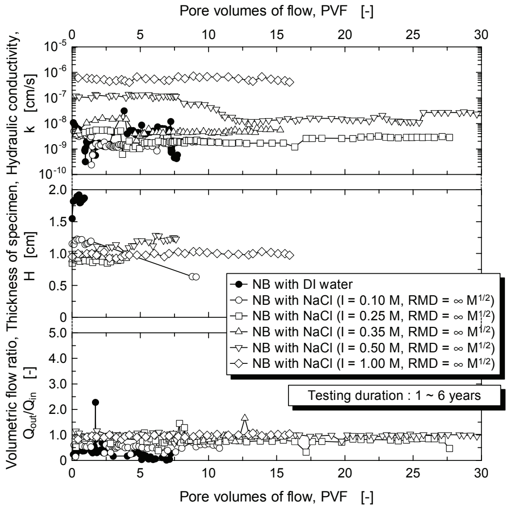

Figure 3. Long-term hydraulic conductivity of granular NB in DI water and NaCl solutions

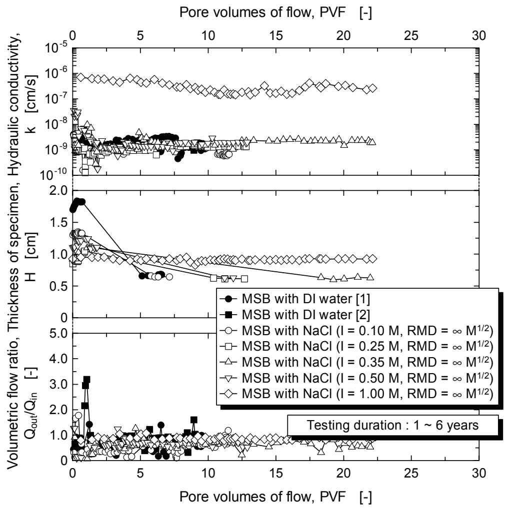

Figure 4. Long-term hydraulic conductivity of granular MSB in DI water and NaCl solutions

Figure 6 shows the hydraulic conductivity values of NB and MSB permeated with a NaCl solution. MSB exhibits a better chemical resistance than NB for the permeation of a NaCl solution with a molar concentration of $\leq$ 1.0 M. However, the hydraulic conductivity of MSB is nearly identical as that of NB when the molar concentration of the NaCl solution is 2.0 M. Figure 7 shows the hydraulic conductivity value of DPH-GCL permeated with a $CaCl_2$ solution. DPH-GCL displays an excellent barrier performance for $CaCl_2$ solutions, regardless of the tested $CaCl_2$ concentration level.

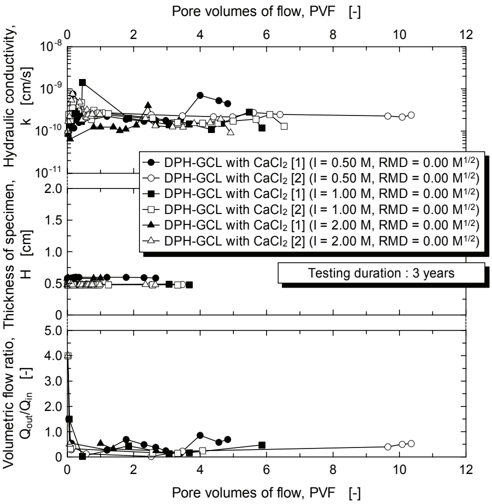

Figure 5. Long-term hydraulic conductivity of powdered DPH-GCL in $CaCl_2$ solutions

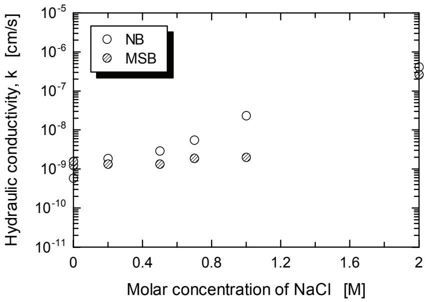

Figure 6. The hydraulic conductivity of NB and MSB permeated with NaCl solution

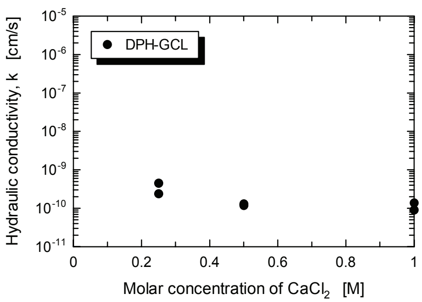

Figure 7. The hydraulic conductivity of DPH-GCL permeated with $CaCl_2$ solution

4 CONCLUSION

This study indicates that (1) multiswellable bentonite (MSB) has sufficient swelling to contain chemical solutions with an ionic strength of $I \leq 0.5$ M. (2) For the permeation of a NaCl solution, the hydraulic conductivity of MSB is lower than that of natural bentonite (NB). MSB exhibits a remarkable chemical resistance for NaCl solutions with a molar concentration of ≤ 1.0 M. (3) 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 $CaCl_2$ solutions with a molar concentration of ≤ 1.0 M.

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