京都大学防災研究所年報　第43号 B-2　平成12年4月
Annuals of Disas. Prev. Res. Inst., Kyoto Univ., No. 43 B-2, 2000

Evaluation of Chemical-Resistant Bentonite for Landfill Barrier Application

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Synopsis

Chemical compatibility of a newly developted material -multiswellable bentonite- is evaluated for the purpose of landfill barrier application. A series of liquid limit, free swell, and hydraulic conductivity tests were performed. The materials used in this study are natural bentonite and multiswellable bentonite. The permeants are distilled water, and $CaCl_2$ and/or HCl solutions. Electrical conductivity and pH values of the effluents obtained from the hydraulic conductivity tests were measured to ensure the total chemical breakthrough. Multiswellable bentonite was found to perform better than natural bentonite does when in contact with $CaCl_2$ and/or HCl solutions. Values of free swell and liquid limit of both bentonites decreased with the increase in concentration of $CaCl_2$. Most specimens of multiswellable bentonite had the hydraulic conductivity one or more orders of magnitude lower than that of natural bentonite when in contact with the same concentration of $CaCl_2$ solutions. The hydraulic conductivity values of both bentonites are higher than the requirement by the US EPA for MSW landfill clay liner ($k < 10^{-7}$ cm/s) when permeated with calcium chloride solution greater than 0.3 M.

Keywords: Chemical compatibility, hydraulic conductivity, geosynthetics clay liner (GCL), multiswellable bentonite

1. Introduction

Waste-containment facilities are required to contain layers of low hydraulic conductivity ($k \leq 10^{-7}$ cm/s) to impede percolation into the waste (cover system) and leachate into groundwater (liner system) (Fig. 1). Compacted clay liners (CCL) have been used for this low hydraulic conductivity layer in USA and European countries. Recently, geosynthetic clay liner (GCL) has also been used for the low hydraulic conductivity layer. GCLs are factory- manufactured

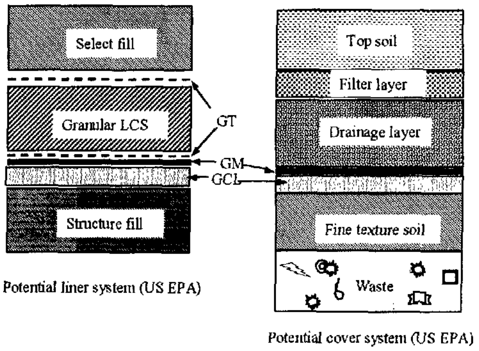

Fig. 1. USEPA regulations for landfill liner and cover.

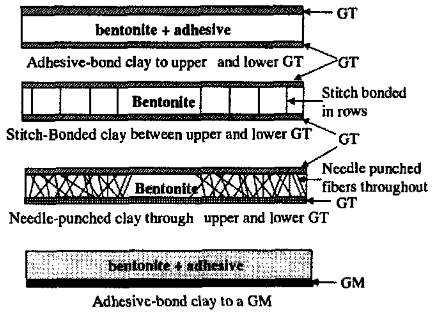

Fig. 2. Cross sections of geosynthetic clay liners.

products that consist of a layer of granular bentonite sandwiched between two geotextiles, or glued to a geomembrane (Fig. 2). The reasons of widespread use of GCLs are their low hydraulic conductivity, and a perceived resistance to environmental distresses such as frost action (Kraus et al. 1997). The low hydraulic conductivity of the bentonite in these liners is attributed mainly to the high swelling potential of the montmorillonite, which is the main component of the bentonite. Bentonite has also been proposed as the additive clay materials for CCL to achieve the low hydraulic conductivity. However, there are several factors that may negatively affect the hydraulic conductivity of GCL and CCL consisting of bentonite, such as cation exchange, dielectric constants, and electrolyte contents (salt contents). For example, Na-bentonite in a divalent solution and sea-water shows limited swelling, and consequently the high hydraulic conductivity that the Na-bentonite could not be used as a barrier any more (Onikata et al. 1996, Ruhl and Daniel 1997, Petrov and Rowe 1997, Jo 1999, Katsumi 1999, Lin and Benson 2000). Thus, several attempts have been made to improve the chemical resistance of bentonite. For example, Onikata et al. (1996) discovered that propylene carbonate (PC) forms complex with montmorillonite, which can activate osmotic swelling of montmorillonite even in aqueous electrolyte solutions.

Therefore, the purpose of this study is to evaluate applicability of chemical-resistant bentonite using PC to landfill liner, mainly GCL. Bentonite portion of geosynthetics clay liners (GCLs) is focused for the experimental study, since the previous study (Jo 1999) indicated that there is little effect of fibers on hydraulic conductivity of GCL.

2. Background

2.1 Natural Bentonite

Bentonite, mainly montmorillonite, is a member of the smectite family (Egloffestein 1995). Montmorillonite possess high swelling potential. Montmorillonite swells in two stages: first, hydration swelling that attract several layer of water molecular between the clay layers inner crystalline swell), and second, osmotic swelling that takes the layers out to large separation distance (McBride 1994). The osmotic swelling takes place only for Na-bentonite (inner crystalline + osmotic swell). In the process of osmotic swell, the Na^+ ions move from their central position in the interlayer to the layer surface and form the so-called electrical double layers. Electrical double layers are mutually repellent. The repulsion of the electrical double layers separate the silicate layers from each other to a greater distance. The thickness of electrical double layer could be affected by electrolyte concentration, cation valence (cation exchange), dielectric constant, the index of pH of the pore solution, and temperature (Mitchell 1993). Bentonite has the high cation exchange capacity. Theoretically, a larger cation tends to displace a small cation, a Na-bentonite may be changed into a Ca-bentonite. A typical exchange series is: $Na^+ < Mg^{2+} < Ca.^{2+} < Al^{3+} < Fe^{3+}$ (Mitchell 1993). However, it can replace a higher power cation with lower power cation by mass action. When the cations in bentonite have been fully exchanged for the cation in the pore water, this leads to a contraction of the interlayers of bentonite. The contraction of the interlayer could decrease the swelling volume and increase the hydraulic conductivity.

2.2 Mutilswellable Bentonite

Bentonite may not show osmotic swelling in high concentration of electrolyte solution or with low concentration of multi-valence solution (Katsumi et al. 1999, Lin and Benson 2000, Shackford et al. 2000). Onikata et al. (1996) discovered that propylene carbonate (PC) can be utilized as a swelling activation material (SAM) to natural bentonite. The osmotic swelling could be activated by PC complex in electrolyte solution and fresh water. The PC-added bentonite is called "multiswellable bentonite (MSB)". For sea water, MSB exhibits the significantly greater swelling power (26.5 mL/2g for Japan See water and

27.0 mL/2g for Pacific Ocean water) than natural bentonite (9.3 mL/2g and 7.0 mL/2g respectively) (Onikata et al. 1996). MSB saturated with Na^+, Ca^{2+}, Mg^{2+}, and Ba^{2+} also showed the swelling power of 30, 19, 26, 25 mL/2g respectively (Onikata et al. 1999).

2.3 Termination Criteria

There are several factors that have to be considered when conducting hydraulic conductivity test on clay liners including GCL permeated with chemical solutions (Shackelford et al. 2000). Among them, "Termination criteria," the criteria for terminating hydraulic conductivity tests, is the most important factor to be considered. The criteria that apply to test with water and with chemicals are different, as recommend by Daniel et al. (1997). In the case of pure water permeation, the ASTM standard recommends that the rates of inflow and outflow should be equal (between 0.75-1.25), the hydraulic conductivity should be reasonably steady (at least one pore volume of flow has passed the samples), and the test should last at least eight hours.

When the hydraulic conductivity tests are conducted with chemical solutions, chemical equilibrium should be achieved before the test is terminated. Permeation should be continued until the chemical composition of the effluent liquid is similar to the influent solution (permeant) and/or the main component, which may affect hydraulic conductivity, appear in effluent liquid in the concentration similar to the influent liquid. Shackelford et al. (1999) suggested a simple, practical, and inexpensive method for determining chemical equilibrium in compatibility tests with electrolyte solutions by using electrical conductivity (EC) and/or pH breakthrough curves as an indicator of chemical equilibrium between influent solution and effluent liquid. For the breakthrough curve, the ratio of the EC and/or pH of effluent and influent should approach one.

3. Experimental Procedures

3.1 Materials Used

Two types of bentonites, natural bentonite (NB) and multiswellable bentonite (MSB), were used in this study. Both bentonites have granular and powder forms. The powder form was used for free swell and liquid limit tests, and the granular one was for hydraulic conductivity tests. NB and the base bentonite for MSB were originally imported from Greybull, Wyoming, USA by Hojun Kogyo Co. Ltd. MSB is processed by Hojun Kogyo Co. Ltd. by adding 25% PC (propylene carbonate) by weight.

The reagents used were distilled water and $CaCl_2$ and HCl solutions. HCl was used to adjust pH to 1 in the same Ca^{++} concentration as pure $CaCl_2$ solutions. $CaCl_2$ and HCl used in this study was obtained from Nacalai Tessque Inc., Japan.

3.2 Test Methods

3.2.1 Index tests

Free swell tests were performed according to ASTM D-5890. Two grams of bentonite has been dusted into calcium chloride solutions in a 100 mL graduated cylinder filled with 90 mL solution. After these two grams of bentonite has been placed into graduated cylinder, the graduated cylinders were filled up to 100 mL. The graduated cylinder is carefully covered without disturbance. The sample should stand at least 16 hours without been disturbed before taking a reading. The reagent waters were distilled water, and 0.01-1.0 M $CaCl_2$ solutions.

Liquid limit tests were conducted according to JIS A 1209 except that the reagent liquid is distilled water, and 0.01 M-1.0 M $CaCl_2$ solutions. The bentonites were soaked in reagent liquid for at least 16 hours before testing.

3.2.2 Hydraulic conductivity test

Granular natural bentonite and granular MSB were used for the hydraulic conductivity test. Bentonite was loosely packed in a mold with a diameter of 10 cm and height of 1 cm. The specimen had a dry density of 7.9 kN/m^3.

Tests were performed according to ASTM D-5084. The tests performed by using flexble-wall permeameters in a falling head constant tail water apparatus with a cell pressure of 20 kPa and an average hydraulic gradient of 80. For the specimen permeated with chemical solutions, they were permeated directly with chemical solutions without prehydration. The tests were terminated after the ratios of electrical conductivity of effluent to that of influent approached to one, and at least 10 pore volumes of flow were achieved. For the specimen permeated with distilled water, the tests terminated after one pore volume of flow was achieved.

The permeants used in this study were distilled water, 0.1, 0.3, 0.4, and 0.5 M $CaCl_2$ solutions. HCl was added to some solutions to achieve pH = 1.

4. Results

4.1 Free Swell

This test enables the evaluation of swelling properties of a bentonite in reagent water for estimation of its usefulness for hydraulic conductivity increasing in geosynthetic clay liner. In general, the higher swelling of bentonite particle means that bentonite has the thicker double layers and the lower hydraulic conductivity can be achieved. This test is to compare the swelling of natural bentonite and chemical-resistant bentonite at the same concentration of calcium chloride solution for various concentrations of calcium chloride solutions (0.01-1.0 M $CaCl_2$).

The results of swell tests were shown in Table 1 and Fig. 3. Natural bentonite and MSB exhibit the same amount of swell (28 mL/2 g) when saturated in distilled water. MSBs have larger swelling power for $CaCl_2$ solution with a concentration lower than 0.5 M. For concentration higher than 0.5 M, both bentonites show almost the same amount of swell (~8.0 mL/2g). Swell values of both bentonites decrease with increase in the concentration of $CaCl_2$ solutions. The amount of free swell for the bentonites soaked in a concentration of calcium chloride solution greater than 0.5 M is similar to the swelling of a Ca-bentonite. Egloffstein (1995) reported that the swelling volume of a natural Na-bentonite (inner-crystalline + osmotic) could go up to eight to fifteen times as much and Ca-bentonite (inner crystalline only) up to two to four times as much. The swelling behaviors are consistent with the double layer theory. The PC complex that activated the osmotic swelling of bentonite caused the thicker double layer and the consequent higher swelling of MSBs.

Table 1. Swell index of natural bentonite and MSB.

Type of reagent	Natural bentonite (mL/ 2g)	Multiswellable bentonite (mL/ 2g)
Distilled water	28.0	28.0
0.01 M $CaCl_2$	32.5	36.5
0.05 M $CaCl_2$	11.0	18.5
0.1 M $CaCl_2$	9.5	13.8
0.2 M $CaCl_2$	9.5	10.0
0.3 M $CaCl_2$	9.5	9.5
0.4 M $CaCl_2$	8.5	9.0
0.5 M $CaCl_2$	8.5	9.0
0.6 M $CaCl_2$	8.0	8.0
0.7 M $CaCl_2$	8.0	8.0
0.8 M $CaCl_2$	8.0	8.0
0.9 M $CaCl_2$	8.0	8.0
1.0 M $CaCl_2$	7.5	7.5
0 M Ca^{++} (pH = 1)	37.0	36.0
0.01 M Ca^{++} (pH = 1)	24.5	30.0
0.1 M Ca^{++} (pH = 1)	9.5	16.0

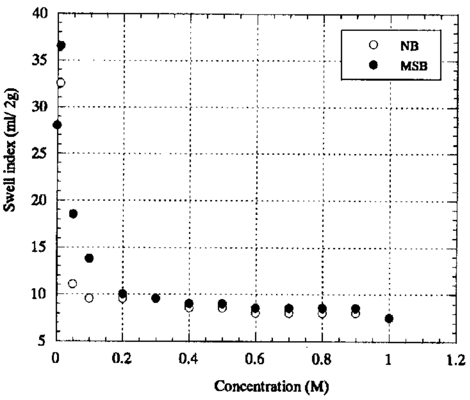

Fig. 3. Swell index of natural bentonite and MSB with various concentrations of $CaCl_2$ solutions.

4.2 Liquid Limit

Understanding the liquid limit behavior of bentonite used for waste containment system and the effect of pore fluid on its liquid limit helps to predict the long-term performance of the system. Bentonite with a higher liquid limit may have better ability to impede percolation, retain leachate and reduce permeability. Hence, the evaluation of index properties of bentonite is important.

MSBs have higher liquid limit for all concentration levels of $CaCl_2$ when compare with natural bentonites, as shown in Table 2. In particular, the difference between natural bentonite and MSB is large (about 40 % difference) for the concentration of $CaCl_2$ lower than 0.5 M, as indicated in Fig. 4. Similar to swelling power, there are not much difference between natural bentonite and MSB for the $CaCl_2$ concentration higher than 0.5 M. Liquid limit also shows a decrease with increase concentration of calcium chloride solution for both bentonites. The decrease of osmotic swelling with an increase in the concentration of electrolyte solution also causes the decrease in the liquid limit of MSB. The finding also coincides with the double layer theory. The higher liquid limit of MSB was activated by the PC complexes as reported

Table 2. Liquid limit of natural bentonite and MSB.

Type of reagent	Natural bentonite (%)	Multiswell bentonite (%)
Distilled water	358.50	391.2
0.01 M $CaCl_2$	311.20	359.9
0.05 M $CaCl_2$	259.60	310.3
0.1 M $CaCl_2$	186.00	261.7
0.2 M $CaCl_2$	183.20	241.8
0.3 M $CaCl_2$	165.40	199.5
0.4 M $CaCl_2$	153.80	176.8
0.5 M $CaCl_2$	145.90	147.1
0.6 M $CaCl_2$	138.90	144.5
0.7 M $CaCl_2$	132.50	141.0
0.8 M $CaCl_2$	125.50	138.9
0.9 M $CaCl_2$	123.20	132.5
1.0 M $CaCl_2$	122.50	130.6
0 M Ca^{++} (pH = 1)	183.6	235.0
0.1 M Ca^{++} (pH = 1)	162.3	206.3

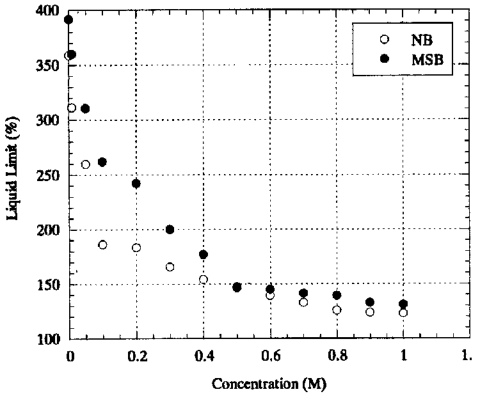

Fig. 4. Liquid limit of natural bentonite and MSB with various concentrations of calcium chloride solutions.

by Onikata et al. (1996).

4.3 Hydraulic Conductivity

The best way to evaluate the performance of a landfill facility is to conduct a hydraulic conductivity test. The hydraulic conductivity tests could simulate the field condition much more appropriately.

Table 3. Hydraulic conductivity values of natural bentonite and MSB.

Type of permeant	Natural bentonite (cm/s)	Multiswellable bentonite (cm/s)
Distilled water	2.8×10^{-9}	1.1×10^{-9}
0.1 M $CaCl_2$	1.4×10^{-8}	1.6×10^{-9}
0.3 M $CaCl_2$	$9 .0 \times 10^{-7}$	1.2×10^{-8}
0.4 M $CaCl_2$	5.0×10^{-7}	4.0×10^{-8}
0.5 M $CaCl_2$	1.2×10^{-5}	6.5×10^{-7}
0 M Ca^{++} (pH = 1)	--	1.5×10^{-9}
0.1 M Ca^{++} (pH = 1)	3.3×10^{-7}	1.4×10^{-7}

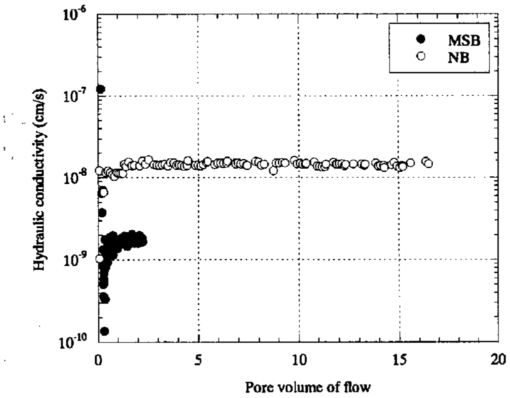

Fig. 5. Hydraulic conductivity values for natural bentonite and MSB permeated with 0.1 $CaCl_2$ solution.

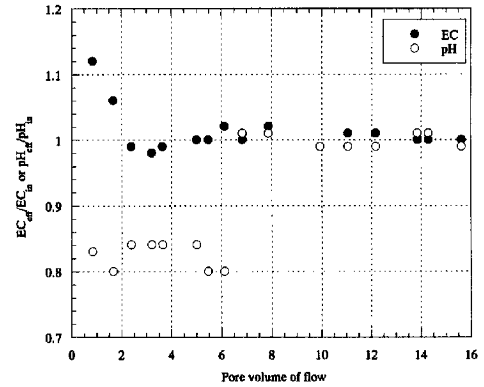

Fig. 6. Normalized electrical conductivity (EC) and pH for the natural bentonite permeated with 0.1 $CaCl_2$ solution.

Hydraulic conductivity values are summarized in Table 3. The specimen permeated with distilled water has the lowest hydraulic conductivity (~10^{-9} cm/s). When permeated with 0.1 M $CaCl_2$ solution, the hydraulic conductivity of MSB (k = 1.6×10^{-9} cm/s) is one order lower than that of natural bentonite (k = 1.4×10^{-8} cm/s), as shown in Fig. 5. Both specimens have lower hydraulic conductivity for the first pore volume of flow, and the hydraulic conductivity then increased up to half of an order of magnitude. The swelling of the bentonite caused the low hydraulic conductivity at the beginning of the test. After the cations had been gradually replaced, the hydraulic conductivity increased. The electrical conductivity and pH of effluent and influent liquids of the natural

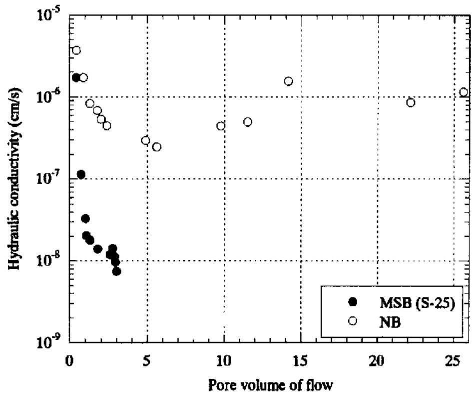

Fig. 7. Hydraulic conductivity of natural bentonite and MSB permeated with 0.3 M $CaCl_2$ solution.

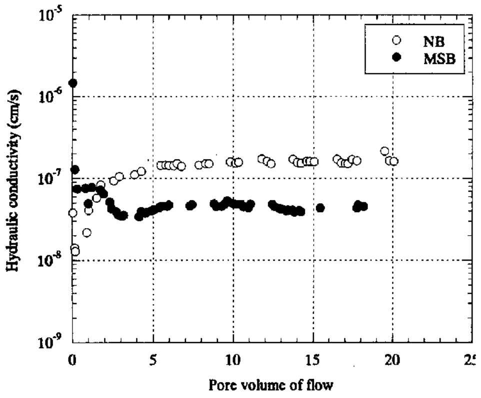

Fig. 8. Hydraulic conductivity of natural bentonite and MSB permeated with 0.4 M $CaCl_2$ solution

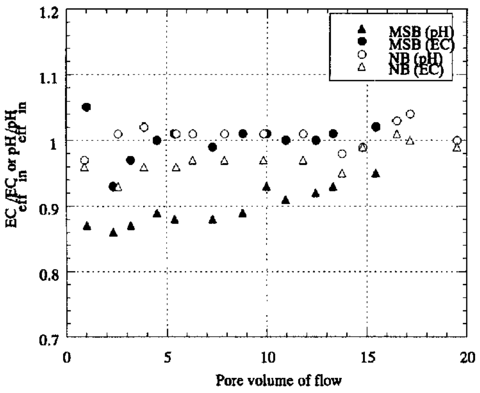

Fig. 9. Normalized electrical conductivity and pH for natural bentonite and MSB permeated with 0.4 M $CaCl_2$ solution.

bentonite specimen had been checked to ensure chemical equilibrium before the test was terminated, as shown in Fig. 6. Up to now, the test of MSB specimen is still being continued.

For the specimens permeated with 0.3 M $CaCl_2$ solution, the natural bentonite specimen decreased at the first five pore volume of flow, the hydraulic conductivity then went up for the rest of the test (k ~ $9x10^{-7}$ cm/s), as shown in Fig. 7. However, the specimen always had a hydraulic conductivity greater than 10^{-7} cm/s. For the MSB specimen, the hydraulic conductivity (k ~ $1.2x10^{-8}$ cm/s) was lower than 10^{-8} cm/s. The test of MSB specimen is still lasting. Since only four-pore volumes of flow were achieved, the test should be continued to check whether the hydraulic conductivity of MSB specimen might increase in the future.

For the specimens permeated with 0.4 M $CaCl_2$ solution, the MSB specimen had a higher hydraulic conductivity than that of nature bentonite at the beginning of the test (Fig. 8). However, the hydraulic conductivity of both bentonites cross over at about two pore volumes of flow. The hydraulic conductivity of MSB specimen stayed lower than that of natural bentonite for rest of the test. Giroud et al. (1997) proposed that, if GCL is used for landfill lienr, it should have a hydraulic conductivity lower than 10^{-9} cm/s, which is equivalent to USEPA regulation for CCL (10^{-7} cm/s for 60 cm thick). The hydraulic conductivity of natural bentonite (k = $4.5x10^{-7}$ cm/s) was higher than this criterion (k < 10^{-9}cm/s) and the hydraulic conductivity of MSB (k ~ $4x10^{-8}$ cm/s) was also higher than the requirement. The electrical conductivity and pH of natural bentonite and multiswellable bentonite had been checked for chemical equilibrium. The normalized electrical conductivity and pH approached one at around fifteen pore volume of flow, as shown in Fig. 9.

As shown in Fig. 10, natural bentonite and multiswellable bentonite had high hydraulic conductivity (> 10^{-7} cm/s) when permeated with 0.5 M $CaCl_2$ solution; however, their hydraulic conductivity behaviors are different. Hydraulic conductivities of both bentonites are high at the beginning of the test. The hydraulic conductivities decrease for about three pore volumes of flow, and then the hydraulic conductivity increased again. For the multiswellable bentonite, the decrease was caused by the osmotic swelling of the bentonite at the beginning of the test. As the cations had gradually been exchanged, the thickness of double layers decreased and the hydraulic conductivity increased.

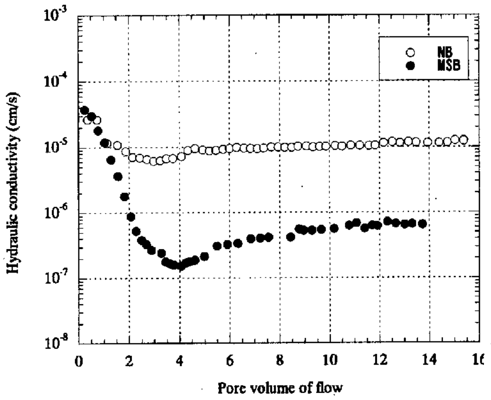

Fig. 10. Hydraulic conductivity of natural bentonite and MSB permeated with 0.5 M $CaCl_2$ solution.

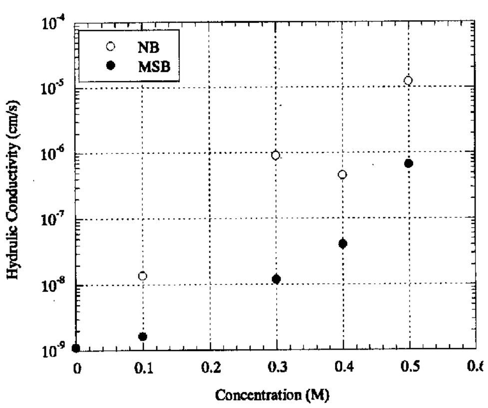

Fig. 11. Hydraulic conductivity test of natural bentonite and MSB permeated with various concentrations of $CaCl_2$ solutions.

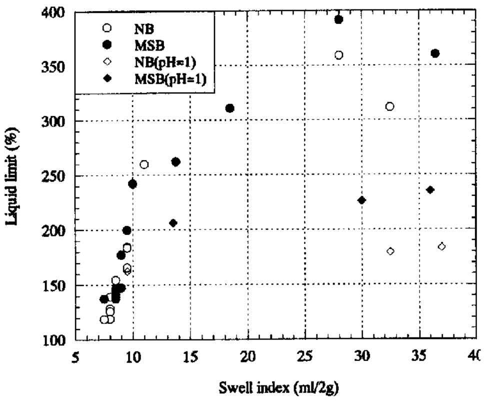

Fig. 12. Comparison between free swell and liquid limit of natural bentonite and MSB.

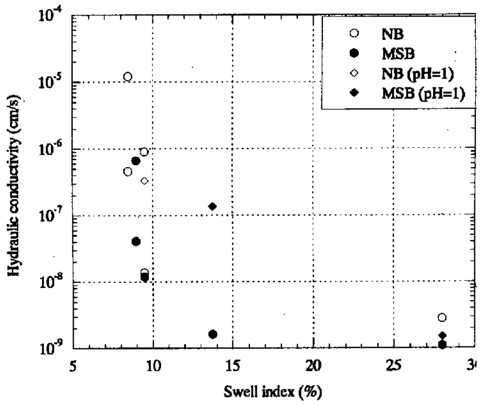

Fig. 13. Hydraulic conductivity values versus free swell of natural bentonite and MSB for various $CaCl_2$ solutions.

Inner crystalline swelling of montmorillonite mainly attributes the decreasing in natural bentonite. The hydraulic conductivity values were kept about 6.5×10^{-7} cm/s for MSB specimen.

Figure 11 summarizes the hydraulic conductivity values for all concentrations of $CaCl_2$. MSB exhibits one or two orders of magnitude lower hydraulic conductivity than natural bentonite for any concentration levels of $CaCl_2$. Thus, MSB is considered as the better alternative barrier materials. However, for the practical application, there are several issues to be solved, such as long-term performance and equivalency to CCL.

As indicated in Table 3, strong acid (pH = 1) had a significant effect on the hydraulic conductivity ($k = 3.3 \times 10^{-7}$ cm/s for natural bentonite and 1.5×10^{-7} cm/s for multiswellable bentonite) when the Ca^{++} concentration is 0.1 M. However, for $Ca^{++} = 0.0$ M, the hydraulic conductivity permeated with pH = 1 solution is approximately 1.5×10^{-9} cm/s for multiswellable bentonite specimen, which is similar to the value for distilled water. Jo (1999) and Katsumi et al. (1999) indicated that GCL having granular natural bentonite exhibits high hydraulic conductivity when permeated with pH = 1 solutions. Thus, MSB is concluded to be more resistant against acid solutions than natural bentonite.

4.4 Comparison between swell index, liquid limit, and hydraulic conductivity

If a soil has the higher swell index, the soil will also show more liquidity. Egloffstein (1995) suggested that the swelling capacity of bentonite depends on the type and concentration of electrolytes solutions. It is coincident with the results obtained in this study. Figure 12 shows the relationship between swell index and liquid limit of natural bentonite and MSB for the same chemical solutions. If natural bentonite or multiswellable bentonite had high swell index for a certain solution, they would have high liquid limit value for the same solution. The free swell and liquid limit decreased with increase in concentration of calcium chloride. In addition, the regression curve between swell index and liquid limit for MSB without HCl is the same as the one for natural bentonite. Thus, the liquid limit can be predicted by the swell index.

As mentioned by Egloffstein (1995), the higher swelling the bentonite has, the lower hydraulic conductivity it posses. Figure 13 summarizes the hydraulic conductivity values versus swell index for the same chemical solutions. From this figure, when natural bentonite or MSB had a higher swell, it posses a lower hydraulic conductivity. Although the data are limited, the regression curve for MSB is considered to be the same as the one for natural bentonite if the permeants are neutral. Plots for the specimens permeated with acid solutions (pH = 1) may have a different tendency; although 0.1 M Ca^{++} solutions with and without HCl result in the same swell index, the solution with HCl results in the hydraulic conductivity ($1.4x10^{-7}$ cm/s) two orders of magnitude greater than the one of the solution without HCl ($1.6x10^{-9}$ cm/s). In conclusion, similar to liquid limit, the hydraulic conductivity values might be predicted from the swell index if the permeants are neutral.

5. Conclusions

Multiswellable bentonite (MSB) performed better than natural bentonite for free swell, liquid limit, and hydraulic conductivity tests. Multiswellable bentonite had a larger amount of swell than natural bentonite had under calcium chloride concentration lower than 0.2 M. Under the calcium chloride concentration higher than 0.2 M, the swell of natural bentonite and multiswellable bentonite were practically the same.

Natural bentonite exhibited lower liquid limit values than multiswellable bentonite. At a calcium chloride concentration lower than 0.4 M, the liquid limit is higher for multiswellable bentonite than for natural bentonite. The liquid limits were almost the same for both bentonites when mixed with calcium chloride concentration greater than 0.4 M.

Hydraulic conductivities of natural bentonite were higher than that of multiswellable bentonite permeated with the same concentration of calcium chloride solution at various of calcium chloride concentrations. In particular, hydraulic conductivity of multiswellable bentonite specimens is significantly lower than natural bentonite when permeated with 0.3, 0.4, and 0.5 M $CaCl_2$. This large dip was considered to be attributed to the osmotic swelling that occur at the first five pore volume of flow. The hydraulic conductivities of natural bentonite were also decreased at the beginning of the test. These decreases were mainly contributed by the crystalline swell, which is the only swelling property Ca-bentonite has.

From this study, the multiswellable bentonite was proved that it performed better than natural bentonite for the purpose of landfill barrier application. However, when the results obtained from this study are compared with the datum on GCL, caution should be taken. For example, the dry mass per unit area (8.3 kg/m^2) of the specimens used in this study is slightly different from the actual GCL (usually 7.5 kg/m^2). Also, the specimens used in this study were bentonites only, without any fabrics and textiles. For the practical application of multiswellable bentonite, there are still several issues need to be solved, such as long-term performance and equivalency to CCL and other regulated liner materials.

6. Acknowledgements

Support was partly provided by Showa Shell Sekiyu Foundation for Promotion of Environmental Research.

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要旨

耐化学性ベントナイトである多膨潤性ベントナイト（mutiswellable bentonite: MSB）の，廃棄物処分場バリア材への適用性を実験的に検討した。MSBは塩化カルシウムや塩酸の溶液に対しても高い膨潤性を示し，透水係数も天然ベントナイトより1オーダー以上低い値が得られたことから，廃棄物処分場のライナーやカバーなどのバリア材に有効に適用しうることが示唆された。

キーワード： 耐化学性，透水係数，ジオシンセティッククレイライナー（GCL），多膨潤性ベントナイト