Chemical effects on the performance of soil-bentonite cut-off walls for in-situ containment

Effets chimiques sur les performances d'un mur parafouille en sol bentonite destiné au confinement in situ

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ABSTRACT
Containment with soil-bentonite (SB) cut-off walls is a valid method to prevent the contaminants in subsurface environment from migrating in the aquifer. This paper addresses the laboratory testing results on the hydraulic barrier performance of SB focusing on its chemical compatibility, since the swelling of bentonite, to which the low hydraulic conductivity (*k*) of the SB is attributed, is significantly influenced by the chemical species and their concentrations in the soil and groundwater. Flexible-wall hydraulic conductivity tests were conducted for SB specimens, which were processed from three different types of soils, exposed to various types and concentrations of chemicals (calcium chloride, heavy fuel oil, ethanol, and/or seawater) in the permeant and/or in the pore water of original soil. For the SB specimens in which the pore water of original soil did not contain such chemicals and thus the sufficient bentonite hydration was expected to occur, *k* values were not significantly increased even when permeated with the relatively aggressive chemical solutions such as 1.0 mol/L $CaCl_2$ or 50%-concentration ethanol solution. In contrast, the SB specimens containing $CaCl_2$ in the pore water had the relatively higher *k* values. For the $CaCl_2$ concentrations higher than 0.05 mol/L or the seawater, approximately one order of magnitude higher *k* values were obtained. The excellent linear correlation between log *k* and swelling pressure of the SB specimens containing various types and concentrations of chemicals implies that the swelling pressure can be a good indicator for the hydraulic barrier performance of the SB.

RÉSUMÉ
Le confinement à l'aide de murs parafouilles en sol bentonite (SB) constitue une méthode valable pour empêcher les polluants du sous-sol de migrer vers la couche aquifère. Cet article aborde les résultats des essais en laboratoire sur les performances d'imperméabilité du SB en se concentrant sur sa compatibilité chimique, étant donné que le gonflement de la bentonite, à laquelle l'on attribue le faible coefficient de perméabilité (*k*) du SB, est fortement influencé par l'espèce chimique et sa concentration dans le sol et dans la nappe d'eau souterraine. Des essais sur le coefficient de perméabilité des parois flexibles ont été menés sur des échantillons en SB, qui ont été traités sur trois types de sols différents, exposés à plusieurs types et plusieurs concentrations de produits chimiques (chlorure de calcium, mazout lourd, éthanol et/ou eau de mer) dans le perméant et/ou l'eau interstitielle du sol originel. En ce qui concerne les échantillons en SB dans lesquels l'eau interstitielle du sol originel ne contenait pas des produits chimiques de ce genre et pour lesquels l'on s'attendait à une hydratation suffisante de la bentonite, les valeurs *k* n'ont pas augmenté de manière significative même lorsque l'on laissait pénétrer des solutions chimiques relativement agressives telles que du $CaCl_2$ à une concentration de 1.0 mol/L ou une solution d'éthanol à une concentration de 50 %. En revanche, les échantillons en SB contenant du $CaCl_2$ dans l'eau interstitielle ont affiché des valeurs *k* relativement plus élevées. En ce qui concerne les concentrations de $CaCl_2$ supérieures à 0.05 mol/L ou l'eau de mer, des valeurs *k* supérieures d'environ un ordre de grandeur ont été obtenues. L'excellente corrélation linéaire entre le log k et la pression de gonflement des échantillons en SB contenant plusieurs types et plusieurs concentrations de produits chimiques implique que la pression de gonflement peut être un bon indicateur des performances d'imperméabilité du SB.

Keywords : chemicals, cut-off wall, hydraulic conductivity, soil-bentonite, swelling pressure

1 INTRODUCTION

In situ containment with the cut-off wall is a valid method to prevent the contaminants in subsurface environment from migrating in the aquifer. Soil-bentonite (SB) is one of the most widely used barrier materials since it can provide extremely low hydraulic conductivity (*k*) values as well as sufficient deformability (e.g. Grube 1992). An in situ construction technique for the SB vertical cut-off wall, which employs the trench cutting and re-mixing deep wall method (Fig. 1) to achieve the good homogeneity of the wall, has been newly developed by the authors previously (Kamon et al. 2006). It is well known that the *k* of bentonite-based materials strongly depends on the chemical component of the permeant and/or the pore water (e.g. Katsumi et al. 2007, Lee & Shackelford 2005), since the swelling of bentonite, to which the low *k* of the SB is attributed, is significantly influenced by the chemical species and their concentrations in the soil and groundwater (e.g. Mesri & Olson 1971). When constructed at the contaminated site or by the seaside, the SB cut-off wall is possibly exposed to the chemicals with considerable concentrations. Thus, in the QC/QA of the SB cut-off wall, chemical effects on its hydraulic performance should be carefully assessed according to the conditions given in the field. However, there is no efficient quality control method of the SB from the viewpoints of hydraulic barrier performance, since it is difficult to measure the *k* of the low permeable material such as the SB directly due to the time and technical limitations.

This paper addresses the laboratory testing results on the chemical effects on hydraulic barrier performance of SB. *k* was measured for SB specimens, which were processed from three different types of soils, exposed to various types and concentrations of chemicals (calcium chloride, heavy fuel oil, ethanol, and/or seawater) in the permeant and/or in the pore water. Based on the empirical correlation between the *k* and swelling pressure of the SB specimens, it was concluded that the swelling pressure can be employed as a good indicator for the hydraulic barrier performance of the SB.

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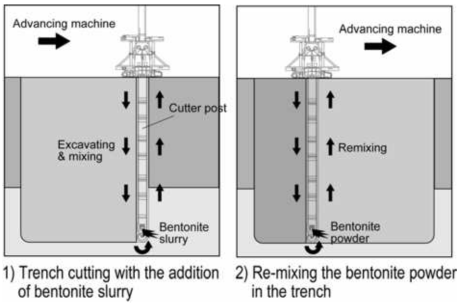

Figure 1 In situ construction of SB vertical cut-off wall by TRD method

2 MATERIALS AND METHODS

2.1 *Materials*

Three different soils were used in the experiment. These soils included 1) a mixture of volcanic cohesive soil and sandy gravel collected at a pilot scale test site (referred to composite soil in the following), 2) silty clay and 3) fine sand. These soils were sieved through a 4.75mm-opening screen. The composite soil was prepared by mixing sandy gravel and volcanic cohesive soil at their natural water contents. The mixing ratio of 25:4 by dry weight (sandy gravel : volcanic cohesive soil) was determined based on the thickness of each layer obtained from the boring log on the pilot test site. Table 1 lists their grain size distributions. Chemical concentration in the pore water was adjusted to the target value. As the divalent cation, Ca^{2+} was selected since it is commonly found in natural aqueous system as well as in water discharged from the industrial process or leached from the waste.

Simulating the process of the wall construction by the TRD method, 10%-concentration hydrated bentonite slurry was firstly blended with the soil. The additive content of the bentonite slurry was determined based on the flowability of the soil-slurry mixture, approximately 150-mm flow value according to JIS R 5201. Once a mixture of suitable flowability was established, 50 to 150 kg/m^3 powder bentonite was added and mixed using the soil mixer.

Table 1 Physical properties of the soil samples used

Soil			Composite soil	Silty soil	Fine sand
Particle size distribution					
Gravel	[2 mm–]	(%)	5.6	0.9	0
Sand	[75 m – 2mm]	(%)	70.8	65.2	87.9
Silt	[5 m – 75 m]	(%)	15.8	19.1	7.9
Clay	[– 5 m]	(%)	7.8	14.8	4.2
Hydraulic conductivity*		(m/s)	1.5 x 10^{-7}	6.4 x 10^{-10}	1.8 x 10^{-7}

* At the consolidation pressure of 40 kPa

2.2 *Hydraulic conductivity test*

After consolidation at 40 kPa in the oedometer, SB specimens having a 30 mm in height and 60 mm in diameter were subjected to the hydraulic conductivity tests. A flexible-wall permeameter with a fallen-head system according to ASTM D5084 was employed. A confining pressure of 30 kPa and a hydraulic gradient of approximately 30-40 were applied during the permeation. Permeation continued until the following four requirements were confirmed: 1) the volume of the effluent and the influent were balanced, 2) the change in *k* values with time was negligible, 3) pore volumes of flow were greater than 3, and 4) the electrical conductivity of the effluent was equal to that of the influent. Testing conditions were summarized in Table 2. P-series was designed to assess the chemical compatibility of the SB attacked by the solution containing the chemicals. In this series, bentonite in SB has been firstly wetted with the pore water of original soil. In the N-series, the expected detrimental effect of the chemicals contained in the pore water of soil was verified, since swelling of the bentonite in the SB is impeded due to the chemicals in the soil in these cases. In the S-series, chemical compatibility of the SB, processed from three different types of soil, was tested.

Table 2. Testing conditions and results of the hydraulic conductivity test

Test No.	Soil type[a]	Chemical concentration in original soil[b]	Chemical concentration of permeant	Hydraulic conductivity, *k* (m/s)
P-00	Co	0	0	5.0 x 10^{-11}
P-10	Co	0	0.1 mol/L-$CaCl_2$	1.9 x 10^{-10}
P-20	Co	0	0.25 mol/L-$CaCl_2$	2.2 x 10^{-10}
P-30	Co	0	1.0 mol/L-$CaCl_2$	1.4 x 10^{-10}
P-40	Co	0	Seawater	1.2 x 10^{-10}
P-50	Co	0	50%-ethanol	4.9 x 10^{-11}
N-00	Co	0	0.1 mol/L-$CaCl_2$	1.2 x 10^{-10}
N-10	Co	0.01 mol/L-$CaCl_2$	0.1 mol/L-$CaCl_2$	2.2 x 10^{-10}
N-20	Co	0.025 mol/L-$CaCl_2$	0.1 mol/L-$CaCl_2$	5.6 x 10^{-10}
N-30	Co	0.05 mol/L-$CaCl_2$	0.1 mol/L-$CaCl_2$	1.0 x 10^{-9}
N-40	Co	0.1 mol/L-$CaCl_2$	0.1 mol/L-$CaCl_2$	1.3 x 10^{-9}
N-50	Co	Seawater	Seawater	9.3 x 10^{-10}
N-60	Co	5,000 mg/kg-heavy fuel oil A	0.1 mol/L-$CaCl_2$	1.0 x 10^{-10}
N-70	Co	10,000 mg/kg-heavy fuel oil A	0.1 mol/L-$CaCl_2$	8.3 x 10^{-11}
S-00	Co	0	0	2.8 x 10^{-11}
S-01	Co	0.01 mol/L-$CaCl_2$	0.01 mol/L-$CaCl_2$	1.0 x 10^{-10}
S-02	Co	0.1 mol/L-$CaCl_2$	0.1 mol/L-$CaCl_2$	1.3 x 10^{-9}
S-10	Si	0	0	2.1 x 10^{-11}
S-11	Si	0.01 mol/L-$CaCl_2$	0.01 mol/L-$CaCl_2$	2.9 x 10^{-11}
S-12	Si	0.1 mol/L-$CaCl_2$	0.1 mol/L-$CaCl_2$	6.3 x 10^{-10}
S-20	Fi	0	0	3.1 x 10^{-11}
S-21	Fi	0.01 mol/L-$CaCl_2$	0.01 mol/L-$CaCl_2$	4.0 x 10^{-11}
S-22	Fi	0.1 mol/L-$CaCl_2$	0.1 mol/L-$CaCl_2$	2.5 x 10^{-10}

[a] Co: Composite soil from the pilot-test site, Si: Silty soil, Fi: Fine sand
[b] $CaCl_2$: concentration in pore water of the original soil
Heavy fuel oil A: concentration in the original soil (dry weight basis)

2.3 *Swelling test*

Swelling pressure of the SB specimen, which had a 20 mm height and was 60 mm in diameter after the consolidation at 40 kPa, under the constant volume condition was measured by using the testing apparatus shown in Fig. 2. During the test, the specimen was submerged in the solution whose composition corresponded to that of the permeant used in the hydraulic conductivity test. The swelling pressure was determined when it reached the maximum value. Cases P-00, S-01, S-02, N-50, N-60, and N-70 shown in Table 2 were tested.

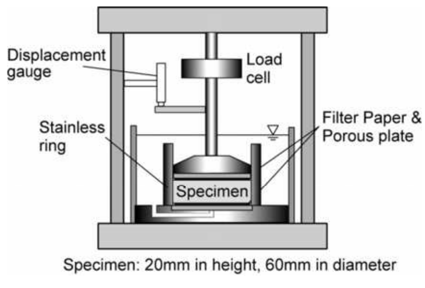

Figure 2 Testing apparatus for measuring the swelling pressure

3 RESULTS AND DISCUSSIONS

3.1 *Effects of chemicals in the permeant*

Figure 3 shows the *k* values in P-series, which were affected by the types and concentrations of chemicals in the permeant. SB permeated with the distilled water had four orders of magnitude lower *k* (5.0 x 10^{-11} m/s) than the original composite soil (see Table 1). The *k* for 0.1mol/L $CaCl_2$ solution was 3.5 times higher than that for distilled water, but still low enough to act as the cut-off wall even against more than 6 pore volumes of flow (Kamon et al. 2006). Effect of the $CaCl_2$ concentration on the *k* was negligible when it was higher than 0.1 mol/L. In the case of 1.0 mol/L $CaCl_2$ solution, *k* value was slightly lower than those for 0.1 and 0.25 mol/L solutions, probably due to the higher viscosity of the permeant. Permeated with the seawater which contains several species of multivalent cations (e.g. calcium, magnesium), the *k* became 1 to 2 x 10^{-10} m/s, which was similar to that for $CaCl_2$ solutions. These observations confirm that the *k* of SB is not significantly increased even against the permeant containing the 1.0 mol/L multivalent cation if the bentonite in the SB is well hydrated with the soil pore water.

For 50% ethanol, *k* was not affected apparently. To take the effect of the high viscosity of ethanol solution into consideration, the intrinsic permeability of the SB was calculated. The obtained value was 1.5 x 10^{-17} m^2 for 50% ethanol, which was only 3 times larger than that for the distilled water, 5.1 x 10^{-18} m^2. This result indicates that the SB was able to maintain its hydraulic barrier performance even when permeated with the high concentration of organic solvents.

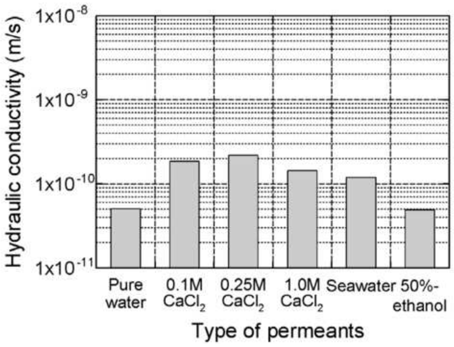

Figure 3 Effect of the chemicals in the permeant on the *k*.

3.2 *Effects of chemicals in the soil pore water*

Figure 4 shows the *k* values obtained in N-series, where the SB contains various types and concentrations of chemicals in the soil pore water. 0.1 mol/L $CaCl_2$ solution was used as the permeant in N-Series, except the case N-50. *k* values were increased exponentially for the $CaCl_2$ concentrations and the *k* for 0.1 mol/L $CaCl_2$ solution reached higher than 1 x 10^{-9} m/s. For the seawater, approximately one order of magnitude higher value was observed by comparing with the SB to which no chemical was added. This increase is equivalent to that caused by 0.05 and 0.1 mol/L $CaCl_2$ solution. However, 5 or 10 g/kg heavy oil in the pore water had no influence on the *k* value.

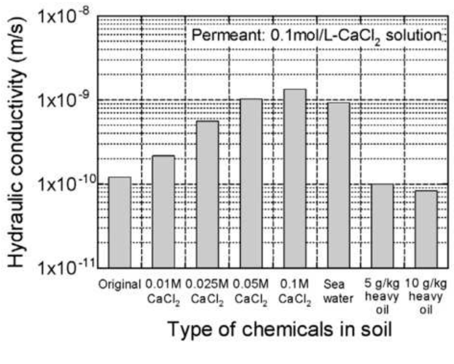

Figure 4 Effect of the chemicals in the soil pore water on the *k*.

By comparing the effects of divalent cations on the *k* when they exist in the permeant (P-series) and in the pore water of the original soil (N-series), the divalent cations in the pore water cause more significant increase in the *k*. The *k* for 0.1 mol/L $CaCl_2$ in the permeant was 3.5 times as high as that for 0 mol/L $CaCl_2$. In contrast, the increase of the $CaCl_2$ concentration in the pore water from 0 to 0.1 mol/L resulted in the increase in the *k* by more than one order of magnitude. These observations indicate that the degree of prehydration of bentonite, which is dependent on the chemical composition of the first wetting liquid (Shackelford et al. 2000), is an important factor for the chemical compatibility of the SB. Thus, the concentration of the divalent cation and its variation in groundwater at the site of concern should be considered in evaluating the hydraulic barrier performance of SB.

3.3 *Effects of soil type*

Figure 5 shows the relationship between *k* values and $CaCl_2$ concentrations in the soil pore water and the permeant for three types of soil in S-series, where the initial $CaCl_2$ concentration in the pore water and the permeant were set equal. For each soil, *k* increased with the concentration of $CaCl_2$. As $CaCl_2$ concentrations increased from 0 to 0.1 mol/L, the *k* values of SBs processed from composite soil and silty clay became 48 and 30 times higher respectively, but the *k* of fine sand based SB was only 8 times higher. Figure 6 shows the relationship between the void ratio after permeation and the $CaCl_2$ concentration. Void ratio of the SB was lowered more significantly by the higher concentration of $CaCl_2$. For a certain $CaCl_2$ concentration, the void ratio of composite soil-based SB was the largest, and those of silty clay-based and fine sand-based SBs were almost equal. Comparing the void ratios for $CaCl_2$ concentration of 0.1 mol/L with those for 0 mol/L, the void ratio of composite soil-based and silty clay-based SBs became approximately 0.2 lower. In contrast, the drop in the void ratio of fine sand-based SB was only 0.1. This trend for the decrease in the void ratio is consistent with the increase of the *k* affected by the $CaCl_2$ concentration shown in Fig. 5.

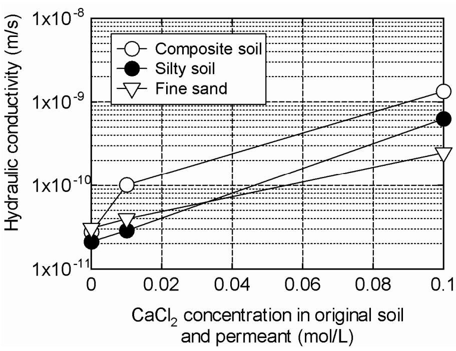

Figure 5 Effects of the $CaCl_2$ concentration on the *k*

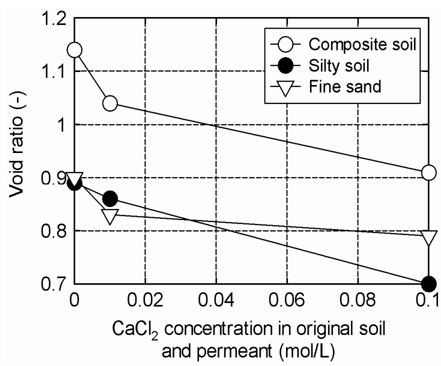

Figure 6 Effects of the $CaCl_2$ concentration on the void ratio of the SB

Figure 7 plots the relationship between the void ratio and the *k*, both of which were normalized with the value for the $CaCl_2$ concentration of 0 mol/L. Correlation between them was observed regardless of the soil type. The lower concentration resulted in the larger void ratio. As a result, larger volume of water is retained as immovable water, which does not contribute to the permeation. This is why the lower k is achieved with the larger void ratio of SB. This finding supports that the void ratio change becomes an important factor for the hydraulic barrier performance of SB attacked by the divalent cation.

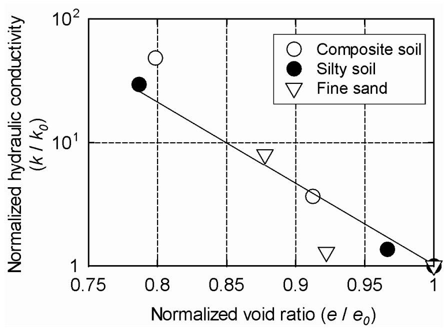

Figure 7 Normalized void ratio vs. k values

3.4 *Swelling pressure as an indicator of the k of SB*

From the previous observations, it can be concluded that the hydration of bentonite is an index of the chemical compatibility of SB. To evaluate the effect of bentonite hydration on the hydraulic barrier performance of SB quantitatively, the swelling pressure, which is representative of the degree of bentonite hydration, was measured for the SB containing various types and concentrations of chemicals. Figure 8 shows the relationship between the swelling pressure (p_s) and log k. A good liner correlation between p_s and log k is observed based on the fact that the relatively lower p_s values were observed for the SBs exposed to the high concentrations of divalent cation, which had the higher k values. Although it takes a long period to measure the k of low-permeable materials such as SB, swelling pressure can be tested within a week or so. Considering this fact, the swelling pressure is expected to be employed as a good indicator for the hydraulic barrier performance of the SB in the QC/QA. To verify the applicability of the swelling test to a simple quality control method, test results on the SB processed from different types of soil and with various bentonite contents, however, should be collected and analyzed.

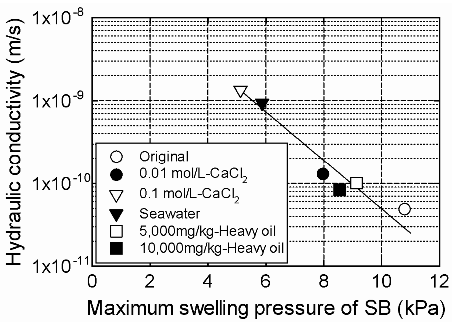

Figure 8 Swelling pressure vs. k of the SB

4 CONCLUSIONS

A series of laboratory tests were conducted to verify the applicability of the SB to the in situ containment cut-off wall from the viewpoint of the hydraulic barrier performance. Particularly, chemical effects on the quality and performance of the SB were assessed in detail. The conclusions obtained can be summarized as follows:

(1) For the SB specimens in which the pore water of original soil did not contain any chemicals and accordingly the sufficient bentonite hydration was expected to occur, hydraulic conductivity (k) values were low enough and not significantly increased even when permeated continuously with relatively aggressive chemical solutions such as 1.0 mol/L $CaCl_2$ or 50%-concentration ethanol solutions. This fact leads the practical implication that the SB cut-off wall can maintain its hydraulic barrier performance in the long term, if constructed at the site where there are no significant concentrations of chemicals in the soil.

(2) SB specimens containing a certain concentration of divalent cation in the pore water had the relatively higher k values due to the restricted bentonite hydration and swelling. The first exposure effects were clearly shown. For the seawater or $CaCl_2$ higher than 0.05 mol/L, approximately one order of magnitude higher k values were obtained.

(3) When the pore of the original soil is filled with the seawater, the SB had more than one order of magnitude higher k value. If constructed by the seaside, the quality of the SB cut-off wall should be carefully considered. In contrast, 10,000 mg/kg-soil or less concentrations of oil in the soil had no adverse effect on the k of the SB.

(4) The negative correlation between the k values and the void ratio in the SB specimen implies that the degree of the bentonite hydration, as well as the volume of immobile water, is an important factor affecting the hydraulic barrier performance of the SB. Actually, the excellent linear correlation between log k and the swelling pressure of the SB was observed regardless of types of soils and chemicals to which the SB is exposed. Considering the fact that it takes a long to determine the k of SB, the swelling pressure test can be employed as a simple quality control method for the hydraulic barrier performance of the SB.

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REFERENCES

Grube, W.E. 1992. Slurry trench cut-off walls for environmental pollution control. In D.B. Paul, R.R. Davidson & N.J. Cavalli (eds), *Slurry Walls: Design, Construction, and Quality Control*: 69-97. Philadelphia: ASTM.

Kamon, M., Katsumi, T., Inui, T., Ogawa, Y. & Araki, S. 2006. Hydraulic performance of soil-bentonite mixture barrier. In H.R. Thomas (ed), *5th ICGE Environmental Geotechnics; Proceedings of the ISSMGE Fifth International Congress on Environmental Geotechnics*, Cardiff, UK, June 26-30, 2006: 733-740. London: Thomas Telford Publishing.

Katsumi, T., Ishimori, H., Ogawa, A., Yoshikawa, K., Hanamoto, K. & Fukagawa, R. 2007. Hydraulic conductivity of nonprehydrated geosynthetic clay liners permeated with inorganic solutions and waste leachates. *Soils and Foundations* 47(1): 79-96.

Lee, J.M. & Shackelford, C.D. 2005. Concentration dependency of the prehydration effect for a geosynthetic clay liner. *Soils and Foundations* 45(4): 27-41.

Mesri, G. & Olson, R.E. 1971. Mechanisms controlling the permeability of clays. *Clays and Clay Minerals* 19: 151-158.

Shackelford, C.D., Benson, C.H., Katsumi, T., Edil, T.B. & Lin, L. 2000. Evaluating the hydraulic conductivity of GCLs permeated with non-standard liquids. Geotextiles and Geomembranes 8: 133-161.