Hydraulic barrier performance of sand-bentonite mixed soil in different hydration condition

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ABSTRACT

A performance of sand-bentonite mixed soil produces low enough hydraulic conductivity to become a landfill barrier material. However, poor-hydration condition and non-homogeneous distribution of bentonite will cause the reduction of barrier performance due to leakage of leachate. The objective of this study is to investigate the effect of Ca^{2+} ion for hydraulic barrier performance of bentonite mixed Toyoura sand in different hydration condition and with various mass ratio of bentonite (MRB = 0, 5, 10, and 15%). The results indicated that partitioning coefficient (K_d) increased while effective diffusion coefficient (D_e) and hydraulic conductivity (k) decreased in the increment of MRB from 0% to 15%. Hydraulic conductivity (k) increased approximately 2-to-4 orders when soil mixture was changed from deionized water to $CaCl_2$ for hydration and permeation in above cases of MRB. The increment in k occurred because Ca^{2+} ion with high ionic strength reduced swelling capacity of bentonite. X-ray Computed Tomography (CT) images for these cases also elucidated this conclusion.

Keywords: sand-bentonite mixed soil; sorption; diffusion; permeability; pre-hydration; X-ray CT image

1 INTRODUCTION

Sand-bentonite mixed soil has been widely used as materials for landfill barriers in recent years (Xu et al. 2018). By admixing bentonite into in-situ soil with high permeability, the mixture can constrain leachate and delay its presence in subsoils and groundwater thanks to its high adsorption and swelling capacities (Mukherjee and Kumar 2018). However, swelling capacity of bentonite can be affected to a great extent by several factors from installation and environment conditions including bentonite percentage (Castelbaum and Shackelford 2009), sand particle size distribution (Kaoser et al. 2006) and leachate (Xu et al. 2018).

Calcium ion (Ca^{2+}) of saline leachate which is considered to possess the high ionic strength enable to limit the expansion of the crystal layers and influence on parameters of hydraulic barrier performance (k, D_e and K_d). Jo et al. 2005 examined that k value of GCLs permeated with strong divalent $CaCl_2$ solution (50mM) was nearly 3 orders higher than that of deionized water (DI) case. However, well pre-hydrated condition of bentonite-mixed sand before permeating with this soluble cation may reinforce pore structure of bentonite component; hence slow flow condition of permeant solution. Pre-hydration condition was paid much attention for geosynthetic clay liners (GCL) containing bentonite. Liu et al. (2015) reported that GCL had 250 times lower k value when pre-hydrated with 140% water content than the non-hydrated sample in case of exposing to 0.5 M H_2SO_4. In case of Japan, the concentration of $CaCl_2$ could be assumed a high level of Ca^{2+} in leachate from an incarnated ash landfill. The objective of this study is to evaluate effects of different pre-hydration condition to immerse in DI water and $CaCl_2$ of sand-bentonite mixed soils before permeating with $CaCl_2$ solutions on hydraulic parameters of k, D_e, K_d. In this study, X-ray Computed Tomography (CT) images allow visualizing internal pore structure of this bentonite mixture during permeability test, thus facilitating to verify swelling capacity of bentonite for each tested specific case.

2 MATERIALS AND METHODS

2.1 Materials

The materials used in the study are mixture of Toyoura sand with low uniform coefficient and sodium (Na)-Bentonite with different mass ratio of bentonite (MRB) 0%, 5%, 10% and 15% as shown in Table 1. Mixing process to prepare samples was conducted in full-dry condition and simultaneously, water and solution was applied to avoid material separation. The solution of $CaCl_2$ with concentration regulated for each test was examined by performing sorption, diffusion, and constant flow rate permeability tests to determine partitioning coefficient (K_d), diffusion coefficient (D_e), and hydraulic conductivity (k) with respect to Ca^{2+} through sand-bentonite mixed liner, respectively.

Table 1. Properties of mixtures of Toyoura sand and bentonite.

MRB (%)	Dry density (g/cm^3)	Porosity (%)
0	1.54	41.7
5	1.62	39.0
10	1.71	35.0
15	1.81	31.0

2.2 X-Ray CT Scanner

Each mixture of sand-bentonite was scanned using a micro-focused X-ray CT scanner (Toshiba co. TOSCANNER 32300 FPD) to determine behavior of soil mixture before and after hydration to DI water and $CaCl_2$. The sample was placed in an aluminum pipe with the height of 60 mm and diameter of 10 mm. In this scan, the voltage and current were set at 180kV and 200 µA, respectively. To observe bentonite behavior and pore structure in the soil mixture, the resolution of 1 voxel equal to 5 µm was obtained in the total range of 1024x1024 voxels. X-ray CT image composes of digital value so called CT-value, which is proportional to the material density. Hence, the behavior of bentonite-mixed sand in different hydration conditions can be evaluated quantitatively from these CT values.

2.3 Sorption and Diffusion tests

The plastic tubes 50ml were filled with the soil mixture and solution $CaCl_2$ with ratio 1:20 for three different concentration of 100, 200 and 300 g/L. The tubes after that were shaken for at least 24 hours to equilibrate and centrifuged at 3000 rpm for 30 min to isolate soils and solution. The pipette was used to take 1 ml sample from this supernatant solution.

Diffusion test was set up using acrylic cell with 100 mm in height and 50 mm in diameter containing compacted soils in 10 mm thickness. The apparatus consists of an upper part of soil sample (source reservoir) full of $CaCl_2$ solution with 30000-32000 mg/L concentration and a lower part of soil sample (receptor reservoir) are full of DI water. A spring with confining pressure of 15kPa was applied at source. Samples of both source and receptor 1 ml were taken after 2 days and replaced with equal volumes of DI water. The concentration of Ca^{2+} for sorption and diffusion tests was analyzed by an ion selective portable-detector for Ca^{2+} so called CA2032. Analytical error was 5% obtained from the used equipment.

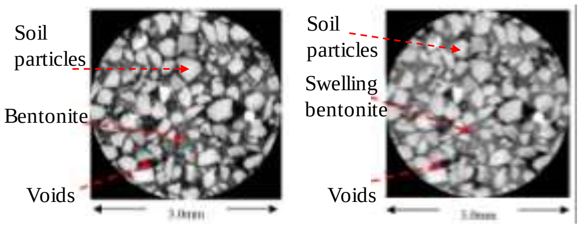
2.4 Constant flow rate permeability test

The apparatus of constant flow permeameter allows the minimum and maximum constant inflow rate of a specific amount of liquid at 3.18 cc/day and 318 cc/day, respectively. Four acrylic cells with 100 mm height and 50 mm inner diameter were subjected to this system for 4 different cases of MRB under the minimum inflow rate. Also, the apparatus provides 4 pressure gauge 1MPa to monitor the pressure change when DI water and/or $CaCl_2$ solution were injected through 4 cells. Based on the recorded pressure, k of each specimen was calculated using Darcy's law. Note that k of specimen with MRB 0% was only obtained from constant head permeability test.

3 RESULTS AND DISCUSSIONS

3.1 Microstructure of bentonite-mixed sand hydrated with DI water and $CaCl_2$

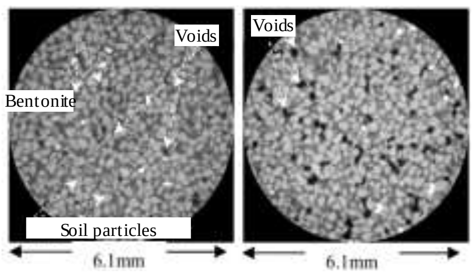
Fig. 1a shows X-ray CT images that bentonite and sand particles can be separated by void space before hydrating DI water. Otherwise, it becomes difficult to recognize this situation when the mixture was then hydrated with DI water (Fig. 1b). In term of DI water, bentonite could swell well enough to fully fill pore space between bentonite and sand particles. Thus, pre-hydration with DI water must have contributed to enhance hydraulic performance of the mixture.



(a) Before hydrating (b) After hydrating

Fig. 1. 2-Dimensional X-Ray CT images of bentonite mixed sand before and after hydrating with DI water.

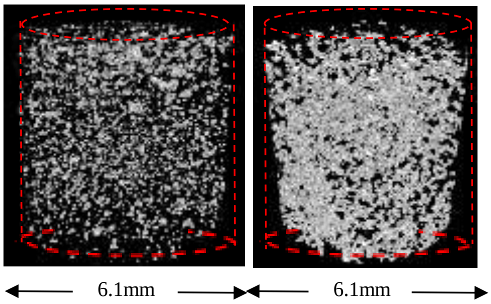
The significant difference between hydration with DI water and $CaCl_2$ solution of the mixture was emphasized through X-Ray CT images for the case of MRB=5% in Fig. 2. In accordance with DI water hydration as shown in Fig. 2a, most voids were covered with swelling bentonite while swelling capacity of bentonite was seen to reduce because of $CaCl_2$ solution, manifested by many voids (black) in the Fig. 2b.



(a) DI water (b) $CaCl_2$

Fig. 2. 2-Dimensional X-Ray CT images of the case MRB=5% hydrated with DI water (a) and $CaCl_2$ (b).

Air void distribution in 3D for the case of MRB=5% was visualized as shown in Fig. 3a and b. The number of voids in term of $CaCl_2$ hydration is much higher than that of DI water. Voids are 817 voids when hydrating with DI water. On the other hand, 1859 voids were counted for the case of $CaCl_2$ hydration. It may become the evidence for the double layer contraction of clay minerals and pore space increase.



(a) DI water (b) $CaCl_2$

Fig. 3. 3-Dimensional X-Ray CT images of the case MRB=5% hydrated with DI water (a) and $CaCl_2$ (b).

3.2 Partitioning coefficient (K_d)

The sorption isotherm in Fig. 4 indicates sorption capacity of bentonite with Ca^{2+} ion. Based on the shape of the isotherm, sorption process was modeled as being liner isopleth. Therefore, the mass of Ca^{2+} removed from solution (S) is proportional to the equilibrium concentration in solution (C_e) as the formula:

$$S = K_{db}\, C_e \tag{1}$$

where K_{db} is the partitioning coefficient (mL/g) of bentonite. K_{db} to Ca^{2+} was calculated in the range of 0.85-0.94 (mL/g). Hence, the equivalent K_d (K_{deq}) value for each case of MRB will be deduced from the formula proposed by Rowe et al. 2005 as follows:

$$K_{deq} = \frac{m_b\, K_{db} + m_s\, K_{ds}}{m_b + m_s} \tag{2}$$

where K_{ds} is the partitioning coefficient of sand; m_b and m_s represent a dry mass of bentonite and sand in the mixture, respectively. In this case, Toyoura sand has no sorption capacity to Ca^{2+}, hence, K_{ds} is equal 0 mL/g.

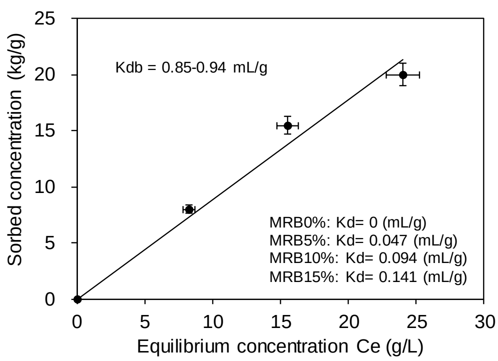


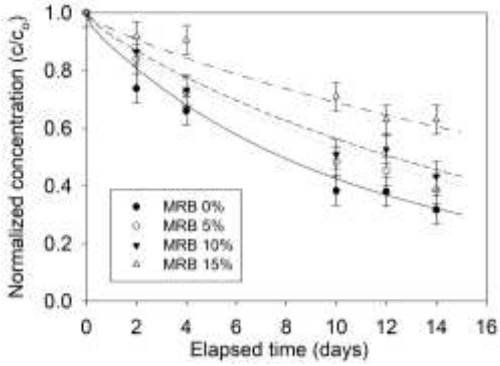
Fig. 4. Sorption of Ca^{2+} ion onto bentonite.

3.3 Diffusion coefficient (D_e)

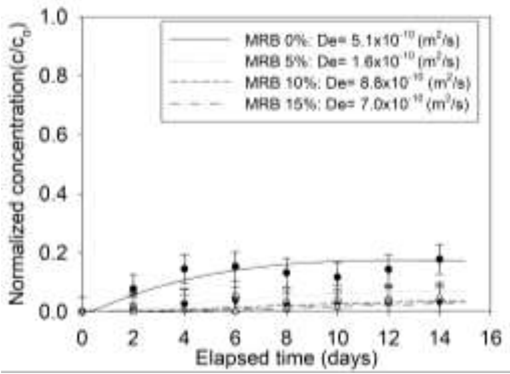
The plots in Fig 5a and b indicate the measured concentration of Ca^{2+} of diffusion experiments for 4 cases of MRB= 0%, 5%, 10%, 15% at source in Fig. 5a and at receptor in Fig. 5b. The error for sample dilution and measurement was recognized to be around 5%, hence the error bars 5% were presented in these below charts as well. So that D_e was obtained, the theoretical model of one-dimensional finite-layer method was used to be applied to fit with experimental data. The results from modeling inferred from running the program POLLUTE (Rowe and Booker 1998) were shown as curve lines in Fig. 5a, b. The one-dimensional partitioning and diffusion equation can be written as:

$$n\frac{\partial c}{\partial t} = nD_e\frac{\partial^2 c}{\partial z^2} - \rho_d K_d\,\frac{\partial c}{\partial t} \tag{3}$$

where c is a concentration at depth z and time t [ML^{-3}]; n = porosity [-]; ρ_d is a dry density of specimen [ML^{-3}].



(a) Source.



(b) Receptor.

Fig. 5. Concentration profile of Ca^{2+}

Fig. 5 shows a reasonable fit between the experimental data and modeling data by POLLUTE for both source and receptor. Hence, the data and curves in Fig. 5a represents the decrement in Ca^{2+} ion concentration at source due to the diffusive flux into the soil samples, meanwhile, the receptor experienced an increment of concentration of Ca^{2+} shown the bottom data and curve in Fig. 5b. Thus, the more bentonite was added, the less the rate of decrease in Ca^{2+} concentration at source but that of increase in Ca^{2+} concentration at receptor.

Fig. 6 illustrates the decrease trend of D_e in the increase of MRB. D_e values dropped from $5.1\text{x}10^{-10}$ m^2/s to $7.0\text{x}10^{-11} m^2/s$ in the increment of MRB from 0% to 15%. Indeed, addition of bentonite to sandy soils contributed considerably to retain Ca^{2+} ion in diffusion

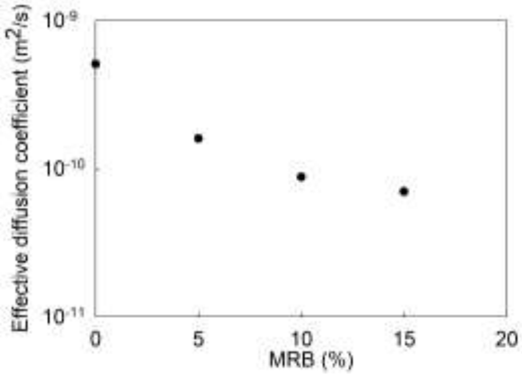


Fig. 6. Trend of De in MRB increment.

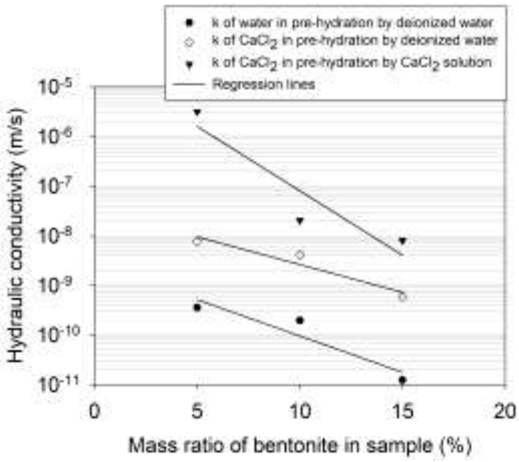


Fig. 7. Hydraulic conductivity of bentonite-mixed sand

migration. However, D_e of MRB10% and 15% are noted to be relatively similar. As the result, the addition of 10% bentonite may be enough for retarding Ca^{2+} diffusive transport in accordance with becoming a suitable material for landfill barrier.

3.4 Hydraulic conductivity (*k*)

Fig. 7 shows the results of k (m/s) in different cases of MRB and hydration condition. The more bentonite addition, the more effective swelling capacity of bentonite when soil samples are hydrated and permeated with DI water. On the other hand, a 10-fold increase in k occurred compared to above-mentioned case because bentonite could not swell completely when permeating with $CaCl_2$ despite pre-hydration of deionized water for all cases of MRB. Under the effect of $CaCl_2$ solution hydration and permeation, k of MRB=5%, 10%, 15% increases rapidly compared to two remain cases. However, the rate of increment is different among these cases. $CaCl_2$ solution causes a 4-order increase of k for MRB5 while the addition of MRB10% produces a 2-order increase and MRB15% generates 3-order greater than the case of DI water hydration and permeation.

It is clearly noted that pre-hydration with $CaCl_2$ solution before $CaCl_2$ permeation still keeps k of MRB15% high, around 10^{-8} m/s. Thus, this high k value could be triggered by the direct permeation with extremely high initial concentration of $CaCl_2$ solution without pre-hydration. However, in the real condition, the liner would initially contact with water or low concentration solution before high one. Hence, it may be concluded that MRB15% should be accepted to become the landfill barrier material because it meets the requirement on landfill standards namely k of 10^{-9} m/s or less in term of pre-hydration with DI water before permeating with $CaCl_2$.

4 CONCLUSIONS

Hydraulic performance of bentonite-mixed sand in different hydration conditions and mass ratio of bentonite was evaluated by means of batch sorption, diffusion, and permeability tests as well as the microstructure visualization by X-Ray CT images. The Results showed that the partitioning coefficient of this mixture increases while diffusion coefficient and hydraulic conductivity decrease in the increment of mass ratio of bentonite. The hydraulic conductivity will rise approximately 2-to-4 order when the mixture was hydrated and permeated from DI water to $CaCl_2$ in the MRB range of 0-15%. Based on hydraulic performance parameters of this mixture, the addition of 15% bentonite may help sandy soil be accepted to become landfill liner material.

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