Influence of cement addition on barrier performance of soil-bentonite cut-off wall

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ABSTRACT

Soil-bentonite (SB) cut-off wall is widely used for controlling seepage and contamination migration due to its extremely low hydraulic conductivity. Low strength and stiffness of SB can lead to high flexibility and deformability during and after construction, which is one of the merits as cutoff walls, but it limits the application of SB walls when higher strength is required. In such a case, cement addition is a possible way to improve the strength and stiffness properties of SB, but this approach can affect its barrier performance. Soluble elements in cement may decrease the swelling of montmorillonite which may increase hydraulic conductivity of SB. Also, cement addition provides alkaline benefits for SB barrier performance. In this study, the influence of adding cement on hydraulic conductivity and sorption performance of SB cut-off wall was evaluated. Hydraulic conductivity of amended SB was studied by using flexible-wall permeameters with the falling head system with distilled water. The batch test is used to discuss the sorption performance against trivalent arsenic. The results show that adding cement will increase the initial hydraulic conductivity for around 10 times, while hydraulic conductivity of groups with 100kg/m³ cement will decrease to 20% after 60 days curing. The sorption performance of SB with cement will increase with amount of cement increase.

Keywords: cement, soil-bentonite, hydraulic conductivity, arsenic, sorption

1 INTRODUCTION

Vertical cut-off wall is widely used in contaminated sites and embankment for preventing contaminants migration or seepage flow (Evans et al. 1994). Since comparing with other materials and methods used in vertical cut-off wall, SB has the following advantages, it is frequently adapted as the barrier materials for cut-off wall. Firstly, montmorillonite in in bentonite can swell when it contacts with water. The swelled bentonite can fill micro pores between soil particles that lead to extremely low hydraulic conductivity of SB (Komine et al. 2004). The typical hydraulic conductivity of SB is as low as $1 \times 10^{-9}$ m/s or even smaller, which can decrease seepage velocity and contain the contamination in situ. Secondly, contrasted to rigid vertical cut-off wall, SB wall has high deformability (Grube 1992) which means SB cut-off wall can maintain continuity with large deformation. It leads that SB may still maintain its soundness even after experiencing dynamic loads such as explosion or earthquake. Thirdly, SB also has great sorption capacity against heavy metal including cesium (Inui et al. 2016), lead (Daniels et al. 2004) and arsenic (Su et al. 2001). Lastly, considering construction, SB cut-off wall still has several benefits. For example, it can immediately work, while concrete wall needs 28 days before reaching its design hydraulic conductivity. Through trench re-mixing and cutting deep method (TRD) method, SB cut-off can also achieve great homogeneity (Katsumi et al. 2008), and the quality control method is also well discussed (Takai et al. 2016).

However, SB cut-off wall still has great limitations in strength and stiffness. Since the SB only consists of in situ soil and bentonite, its strength cannot increase significantly unlike soil-cement mixture. According to previous researches, SB has quite poor strength mechanical performance. Even after long-term consolidation and aging, the typical shear strength of SB cut-off wall is 10 kPa (Evans and Ryan 2005).

Although there have been already several studies about strength improvement of SB, the main method is focused on using cementitious material as another main content rather than additive. The content ratios of cementitious material in the previous studies are over 10% up to 20%. For example, in the United Kingdom, slag-bentonite cut-off walls with 20% cementitious materials are widely used. Its unconfined compression stress (UCS) can be up to 400kPa after 28 days curing (Opdyke et al. 2005). In the United States, cement-bentonite (CB) slurry cut-off wall (cement 15%) is frequently used (Jeffers 2005). These improvements in strength usually come with the increase of hydraulic conductivity to $10^{-8}$ m/s, and the amended SB materials
also lose its deformability. The deformation behaviour of the amended SB is closer to concrete instead of soil (Ata et al. 2015). There are few researches about soil-cement-bentonite (SCB) cut-off wall approaching for moderate strength and hydraulic conductivity (Ryan and Day 2002).

Previous studies mainly focus on large amount cementitious material to greatly improve the strength and stiffness of SB, without enough attention to possible influence on sorption capacity. Since cementitious material will create an alkaline condition which benefits the barrier performance of bentonite (Tang et al. 2015), while it may also cause several negative influences due to lower swelling capacity of bentonite. Therefore, in this study, we investigated the effect of cement addition on the barrier performance of SB, with relatively low content ratio of cement material.

2 MATERIALS

The preparation of SB samples was determined in consideration of an on-site construction process by the TRD method. Decomposed granite soil consolidated under 20 kPa with dry density 1.62 g/cm$^3$ (22% water content) was taken as ground soil in this study because it is widely distributed in Japan including Kyoto. Portland cement was used as cementitious additive and Na-bentonite was used as the additive. The preparation of SB sample can be divided into 4 steps. Firstly, mixed dry decomposed granite soil with water to achieve same water content as nature ground soil. Then poured bentonite slurry (bentonite concentration is 5%) for simulating the excavation process. The third step was adding bentonite powder and mixing that for around 10 mins. Finally, cement powder was added by 4 shares. Then, SB samples were consolidated in oedometer cell ($\phi$ 6.0 cm × H 2.0 cm) under 39.2 kPa for 2 days. The proportions of each material used in the experiments are summarized in Table 1. Void ratio of the samples after consolidation is decreasing with the cement content increasing.

![Fig. 1. Schematic view of a flexible-wall permeameter (Takai et al. 2016).](image)

Table 1. Mixing ratios of SB in this study.

| Group  | Bentonite slurry (L/m$^3$) | Bentonite powder (kg/m$^3$) | Cement powder (kg/m$^3$) | Void ratio |
|--------|-----------------------------|-----------------------------|--------------------------|------------|
| A      | 0                           | 0                           | 0.85                     |            |
| B      | 0.65                        | 50                          | 1.00                     |            |
| C 350  | 0.75                        | 75                          | 0.66                     |            |
| D      | 0.90                        | 100                         | 0.69                     |            |
| E      | 1.17                        | 100                         | 0.65                     |            |

NaAsO$_2$ solution was selected as contamination because arsenic is widely distributed in Japan (Jung et.al 2004) and China (Rodriguez-ladoet al. 2013) naturally and anthropogenically. It has been causing serious drink water pollution and disease in many countries including China (Sun 2004). There are already several projects using SB to immobilize arsenic contamination (Minja and Ebina 2003). Since comparing with pentavalent arsenic, trivalent arsenic has much higher poisonousness. Trivalent arsenic is chosen as contamination in this study.

3 METHODOLOGIES

3.1 Hydraulic conductivity test

Since the predicted hydraulic conductivity is around $10^{-9}$ to $10^{-10}$ m/s, a flexible-wall permeameter with a falling head system was used to evaluate the hydraulic conductivity of amended SB samples according to ASTM D5084-03, as shown in Fig. 1. Hydraulic conductivity can be calculated with the following equation:

$$k = 2.3\frac{al}{A(t_2-t_1)\log \frac{H_1}{H_2}}$$

where, $k$ is hydraulic conductivity, $a$ is cross-section area of the standpipe, $l$ is the height of soil sample, $A$ is cross-section area of soil sample, $t_2-t_1$ is a measurement time, and $H_1$ and $H_2$ is a water level at $t = t_1$ and $t_2$, respectively.

Cell pressure of 40 kPa was applied, and distilled water was used as permeant solution. After consolidating under 39.2 kPa for 48 hours, the specimen was submerged in distilled water and saturated by vacuum deaeration for 24 hours. Then, the specimen was set on the flexible wall permeameter.

3.2 Batch test

The preparation of amended SB sample was similar to the hydraulic conductivity test. Samples were crushed to smaller than 2 mm and mixed with the NaAsO$_2$ solution with a liquid to solid (L/S) ratio of 10. The concentration of NaAsO$_2$ solution is 0.1, 0.5, 1, 5 and 10 mg/L. The samples were subjected to horizontal shaking at 150 rpm for 24 hours, then left for 15 minutes. The solid-liquid separation was done by centrifugation under 3,000 rpm for 10 mins and filtering using a 0.45 μm membrane filter.
Cation concentrations of the solution before and after batch test are analyzed by inductively coupled plasma (ICP) method (Agilent Technologies, 700 Series ICP-OES) and atomic absorption spectrometry (AAS) method (SHIMAZU, AA-6800). The experiment condition is shown in Table 2.

### Table 2. The experiment conditions in batch test.

| Group | Curing time (days) | Shaking speed and time | L/S ratio |
|-------|--------------------|------------------------|-----------|
| Group A | 7                  | 150 rpm 24 h           | 20        |
| Group B | 7                  | 150 rpm 24 h           | 20        |
| Group C | 7                  | 150 rpm 24 h           | 20        |
| Group D | 7                  | 150 rpm 24 h           | 20        |
| Group E | 7                  | 150 rpm 24 h           | 20        |

### 4 RESULTS AND DISCUSSION

#### 4.1 Hydraulic test

The change in hydraulic conductivity of SB with time and pore volume of flow is shown in Fig. 2.

![Hydraulic conductivity of SB along with time.](image)

**Fig. 2.** Hydraulic conductivity of SB along with time.

Since duration of hydraulic conductivity test Group A (without cement addition) is too short by now, not enough amount of leachate was collected to draw a line as other groups, therefore, it is shown in-dash line only to provide a comparison with other groups. From this figure, it can be found that the hydraulic conductivity of SB amended with cement is much higher. After adding cement, the initial hydraulic conductivity of Group B, C and D (with 115 kg/m³ bentonite) increased to $10^{-9}$ m/s. The reason may be explained by that swelling capacity of bentonite was seriously decreased due to binding effect of Calcium-Silicate-Hydrate (C-S-H). However, after keeping contacting with water, due to the curing effect, the C-S-H and CaCO₃ would make up the void between soil particles. The hydraulic conductivity of SB with 100 kg/m³ decrease to almost one-tenth comparing to initial state after 60 days. Also, if lower hydraulic conductivity is expected, increasing bentonite amount may be a suitable method. In Group E, content ratio of bentonite increases from 115 kg/m³ to 135 kg/m³, which lead to 80% decrease of hydraulic conductivity for both initial and final state. According to these results, the swelling capacity of bentonite still dominates the barrier performance in hydraulic conductivity of SB with less than 100 kg/m³ cement.

#### 4.2 Batch test

For each content ratio (Group A, B, C and D) batch sorption tests were conducted in triplicate. Electric conductivity (EC), the potential of hydrogen (pH), cation concentration in arsenic solution including sodium, calcium and iron was measured before and after test to discuss the sorption capacity of SB. Based on the results of solution after batch test, the proprieties of solution have no relationship with arsenic concentration. Most contents don’t have significant changes comparing with the state before test.

![Ca concentration after batch test.](image)

**Fig. 3.** Ca concentration after batch test.
The Ca concentration of solution at each initial As concentration is illustrated in Fig. 3. The Ca cation is decided by the content ratio of cement. Fig. 4 shows the Fe concentration of solution after the test for different initial As concentration. However, when the amount of cement addition in SB is over 75 kg/m$^3$, there is almost no change in Fe concentration. Fe concentration in solution mixing with Group C and D are both around 45 ppm. The increase of Fe cation may benefit the sorption performance of SB amended with cement. The previous study shows that Fe cation may form FeH$_2$AsO$_3$ or FeHAsO$_4^-$ on the surface of the soil, which greatly improves the sorption capacity of iron oxide minerals against arsenic (Dixit and Hering 2003). In this study, the increase of Fe cation in solution reflects this mechanism may exist in enhanced SB samples.

The EC of solution after batch test is shown in Fig. 5. It reflects that EC of the solution after batch significantly increases no matter whether cement is added. For Group A, the EC increase to around 20 mS/m. This increase mainly relies on the around 30 ppm Na cation in the solution after sorption test. While, for groups with cement addition, the change is more noticeable. With the content ratio of cement increased from 50 kg/m$^3$ to 100 kg/m$^3$, the EC also increase from approximately 60 mS/m to near 90 mS/m. Iron and calcium cation contribute to this significant increase in Group B, C, and D. The increase of EC with cement content ratio may be no longer as significant as that in low concentration.

The pH of solution before and after test is shown in Fig. 6. Initial pH of each arsenic solution without adjustment ranges from 7 to 8. The difference in pH value of the solution after mixing with SB is not as clear as that change in EC. The solution after mixing with the Group A with no cement addition only has a slight increase to around 9, which still can be recognized as a neutral condition. While the other type is the solution mixed with amended SB, the pH increases to around 11.5. The pH of this solution does not have clearly relationship with the cement content ratio. Even in Group D, the cement amount is twice as Group B, the pH value is still almost the same.
Sorption isotherms of SB with cement addition and SB without cement and fitting curve are shown in Fig. 7. In this figure, the relationship between sorption amount and equilibrium concentration of SB is exponentiation function. The sorption amount concentration is calculated by:

\[ S = (C_0 - C_{eq}) \times V / m \]  

where, \( C_0 \) is the initial concentration of arsenic solution (ppm), \( m \) is the mass of the sorbent (g), \( V \) is the volume of the solution (L). Sorption isotherm curve is closer to Freundlich model. The equation shows as follows:

\[ q_s = K_F C_{eq}^n \]  

where, \( K_F \) and \( n \) are constant for given adsorbate and adsorbent. The coefficient of determination \( R^2 \) equals to 0.94, 0.94, 0.95, 0.86 for Group A, B, C and D, respectively.

The sorption amount of SB with different cement ratio was calculated under the same hypothetic equilibrium concentration to evaluate the sorption capacity using sorption isotherms. 0.01 ppm is taken as equilibrium concentration based on the requirement of Japanese environmental standard about arsenic. The results of sorption amount of each group when assumed equilibrium concentration is 0.01 ppm are shown in Table 3. These calculation results reflect that sorption performance of SB with over 75 kg/m^3 cement is better than SB without cement even in very low concentration.

| Cement amount (kg/m^3) | Sorption amount (mg/g) |
|------------------------|------------------------|
| Group A 0              | 6.6\times10^{-4}       |
| Group B 50             | 5.4\times10^{-4}       |
| Group C 75             | 1.3\times10^{-3}       |
| Group D 100            | 1.9\times10^{-3}       |

The change in sorption trend means that the sorption mechanism has been changed after adding cement. Adding 75 or 100 kg/m^3 cement will bring greatly increase to the sorption capacity of amended SB comparing with SB samples without cement. While after adding 50 kg/m^3 cement, the sorption capacity of SB almost has no change for 7 days curing.

For SB without bentonite, the isotherm is clearly closer to Freundlich isotherm. The sorption amount is in an exponential relationship with contamination concentration. Mar et al. (2013) mentions that pure bentonite also has an exponential sorption curve against trivalent arsenic. Sorption of bentonite relies on the high specific surface area of bentonite.

After adding cement, the sorption performance of SB is dominated by cement instead of bentonite. There are two different sorption mechanisms for arsenic when using cementitious material as the sorbent. First is the generation of low solubility substance such as CaHAsO_3 by calcium and arsenic. Iron cation also contributes to the co-precipitation of arsenic (Dixit and Hering 2003).

The reason why adding 50 kg/m^3 sorption capacity almost has no change, may be due to the changes in the sorption mechanism. While after adding cement, the binding function of C-S-H gel significantly change particle size distribution. Based on experiment results, after adding 75 kg/m^3 cement, the void ratio of SB samples decreases from 0.85 to 0.66 comparing with SB samples without cement, which shows the structure also has been changed. The C-S-H may bond the fine particle, restrict the swelling performance of bentonite. Adding cement may lower the sorption capacity of bentonite, while the sorption capacity for 50 kg/m^3 is close to the sorption of 115 kg/m^3 bentonite without cement.

5 CONCLUSIONS

By the results of hydraulic conductivity and batch test, using cement as additive has multiple influences on barrier performance of SB. First of all, cement addition has significant negative influence on short-term hydraulic conductivity. C-S-H gel generating by hydration reaction of cement restricts swelling of bentonite and increases particle size. For long-term consideration, when the amount of cement addition is over 100 kg/m^3, hydraulic conductivity of SB will decrease to one-tenth of initial state after 60 days.

From the viewpoint of sorption performance, for SB without cement, it has certain sorption capacity against arsenic. After adding cement, the sorption capacity due to the high specific surface area of bentonite may be removed. The main sorption mechanism changes to the surface attraction of C-S-H and reaction with cement components to form calcium–arsenic or iron-arsenic compounds. When the content ratio is 50 kg/m^3 after curing for 7 days, the sorption capacity of amended SB is close to bentonite. While with the increase of content ratio of cement, the sorption capacity of amended SB significantly grows.
ACKNOWLEDGEMENTS

The authors wish to acknowledge to Mr. N. Ukaji (Raito Kogyo Co., Ltd.) for his valuable suggestions on this manuscript.

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