Engineering properties of soil-cement mixture improved with recycled fine additives for cutoff wall construction

Yuelei Li, Toshihiko Miura, Akira Shinmura, Shuji Miyaoka, Toru Inui and Takeshi Katsumi

i) Graduate School of Global Environmental Studies, Kyoto University, Yoshida-honmachi, Sakyo-ku, Kyoto, Japan.
ii) Obayashi Corporation, 4-640, Shimokiyoto, Kiyose-shi, Tokyo, Japan.

ABSTRACT

Basic engineering properties including fluidity, breeding characteristics, unconfined compression strength and hydraulic conductivity are evaluated for soil-cement mixtures for diaphragm wall construction. The specific objective is to assess the effects of 1) adding three different recycled fine additives including foundry dust, concrete powder and gypsum-rich slag, and 2) mixing with seawater on these engineering properties. Although addition of these fine additives decreased the fluidity of soil-cement slurry, adding the appropriate amount of fine additives increased the unconfined compression strength and decreased the hydraulic conductivity of soil-cement mixture after 28 days aging. Furthermore, using seawater instead of fresh water can also improve the strength and hydraulic barrier performances of soil-cement mixture. These results verify the applicability of these recycled fine additives and seawater to soil-cement diaphragm wall construction.

Keywords: soil cement, diaphragm wall, industrial by-products, seawater

1 INTRODUCTION

Low permeability vertical walls are widely used to control groundwater flow for in situ containment (Katsumi et al. 2008, Joshi et al. 2010, Ruffing and Evans, 2014). Soil cement diaphragm technology is the most widely employed method to construct vertical walls in Japan, since soil-cement mixture has high shear strength and low hydraulic conductivity. In traditional practice for soil-cement wall construction, in situ soil mixing with cement, water (cement slurry) and other fine additives such as bentonite is executed, to restrain the solid-liquid separation in cement slurry and improve the engineering properties. Recently, as a replacement of fine additives, fine industrial by-products such as recycled concrete powder and ground slag have been used as the material. In addition, use of sea water as mixing water is sometimes required due to limited availability of fresh water in construction sites of concern. Many previous works have assessed the unconfined compression strength (UCS) and hydraulic conductivity of soil-cement improved with fine additives (Katsumi et al. 2002, Uchiyama and Kuroda 20012003). However, there is a limited part research on the effects of adding recycled fine additives, which were processed from industrial by-products, as well as mixing with seawater on the engineering properties of soil-cement mixture.

In this study, recycled concrete powder, foundry dust, and gypsum slag were applied as fine additives for soil-cement mixture. Fluidity, breeding characteristics, UCS and hydraulic conductivity were tested for the soil-cement mixtures containing these fine additives with various mixing proportions. Compared with the results for the mixtures composed of soil, cement slurry and bentonite only, applicability of these recycled fines as an alternative or a replacement of bentonite was investigated. In addition, both tap water and simulated seawater were used as mixing water to evaluate the effect of seawater on the engineering properties of soil-cement mixture.

2 MATERIALS

To simulate the cutoff wall construction in a permeable aquifer, gravelly sand (SG), which was collected at a mountainous area and sieved with a screen of 10 mm opening, was used as a host soil for soil-cement. The bulk density and natural moisture content of the sand were 1.7 g/cm3 and 2%, respectively.

As recycled fine additives, three types of recycled fine materials, foundry dust (FD), gypsum-rich slag (GS), and concrete powder (CP), were used. FD is generated from foundry sand-casting process and contains 30 to 40% montmorillonite in dry mass basis. CP is generated from recycling process of demolished concrete. As a conventional fine additive, Akagi bentonite (B), which is Ca-based bentonite, was also used. Particle density and particle size distributions of

http://doi.org/10.3208/jgssp.JPN-30
these soil and additives are summarized in Table 1.

Portland blast-furnace slag cement (SC), Type B (according to JIS R 5210 (2009), Type B SC contains the blast furnace slag in 30 to 60% in dry mass basis) is used as the primary cementitious material, since SC is more resistant to seawater than other cement materials. As mixing water, tap water and simulated seawater (3.3% NaCl solution) were used.

Table 1. Particle density and particle size distributions of host soil and fine additives.

| Materials     | Gravely sand (SG) | Akagi bentonite (B) | Foundry dust (FD) | Gypsum-rich slag (GS) | Concrete powder (CP) |
|---------------|-------------------|---------------------|-------------------|----------------------|----------------------|
| Particle density (g/cm³) | 2.716            | 2.633               | 2.195             | 3.578                | 2.688                |
| Gravel fraction (%) | 24.6             | 0                   | 0                 | 0                    | 0                    |
| Sand fraction (%) | 74.2             | 5.1                 | 40.7              | 27.4                 | 1.5                  |
| Silt fraction (%) | 4.01             | 26.6                | 46.2              | 88.4                 |                      |
| Clay fraction (%) | 54.8             | 32.7                | 26.4              | 10.1                 |                      |

3 TEST METHODS

3.1 Mixing design based on table flow and bleeding ratio tests

Soil-cement mixtures were prepared with various proportions of SC and fine additives. The soil was mixed with them and 360 kg/m³-soil mixing water in 5 minutes by using a soil mixer. The mixtures were subjected to table flow and bleeding ratio tests.

Table flow test according to JIS R 5201 (1997) was conducted for the mixture immediately after mixing, to determine the fluidity of soil-cement mixture, which influences the workability of soil-cement construction. Generally, higher flow values are desirable for wall construction in clay layers. However, too high flow values in construction in sand gravel layers may cause solid-liquid separation, which is the main cause for heterogeneity in soil-cement wall. According to past field experiences, acceptable flow values were set 170 to 230mm in this study.

Bleeding ratio test according to JSCE-F522 (1994) was conducted for the mixture after it was stored in 3 hours. Bleeding ratio is an index for the degree of solid-liquid separation. In this study, an acceptable bleeding ratio was set less than 2%.

Soil-cement mixtures which have both acceptable table flow value and bleeding ratio were subjected to unconfined compression and hydraulic conductivity (HC) tests after curing. The mixing proportions of the specimens for unconfined compression and HC tests are summarized in Table 2. Test specimens were prepared by pouring the mixture in layers into a mold with 50 mm in diameter and 100 mm in height. Then, they were wrapped with moisture proof bags and stored in a humid room to be cured for 28 days.

3.2 Unconfined compression test

Unconfined compression tests were carried out according to JGS 0511 (2009), with a constant stress increment rate of 20 kPa/s. Prior to the test, gypsum dehydrate paste was smeared on the top and bottom sides of all cylindrical specimens to remove the effect of irregular surface. Target UCS value was set 1,000 kN/m² after 28 days curing.

3.3 Hydraulic conductivity test

Hydraulic conductivity test was conducted according to ASTM D 5084 (2010). This method is applicable to the soils with hydraulic conductivity less than approximately 1 x 10⁻⁸ m/s such as soil-cement mixture, since a certain confining pressure is applied to the specimen during permeation to minimize sidewall leakage. The target hydraulic conductivity was set lower than 1 x 10⁻⁸ m/s in this study.

Table 2. Mixing proportions (per 1 m³ sand) of the specimens for UCS and HC tests.

| SC (kg) | Water Type | Fine additives |
|--------|------------|----------------|
| 150    | Tap water 360 | BC = 20/40/60   |
| 150    | Sea water 360 | BC = 20/40/60   |

4 RESULTS AND DISCUSSIONS

4.1 Physical properties of fresh soil-cement

Figure 1a) show the table flow values and bleeding ratios of fresh soil-cement for various contents of fine additives and BC = 200 kg/m³. For the cases in which the bentonite was added, the higher bentonite content led to the smaller flow values. For B = 60 kg/m³, the flow value reached approximately 170 mm, which is the lower limit of acceptable range. The bleeding ratios also decreased with the bentonite content. The bleeding ratio was below 2% when 40 kg/m³ or more bentonite was added. FD had an effect similar to the bentonite. Adding FD decreased the flow values and bleeding ratios of the soil-cement. This is attributed to the composition of FD, which contain 30 to 40% montmorillonite.

However, there was no clear influence of CP and GS addition on flow values and bleeding ratios. Particularly, the bleeding ratios were higher than 2% in all the cases in which CP and GS was added as an alternative of bentonite. To achieve the bleeding ratio of less than 2%, additional mixing tests were conducted for the CP and GS cases by adding 20 kg/m³ of bentonite with SC = 150 kg/m³. The results of
additional tests are shown in Figure 1 b). With a help of 20 kg/m³ bentonite, the higher GS content led to the smaller flow values and the lower bleeding ratio less than 2% successfully. However, for the CP cases, there was still no effect on the bleeding ratio, although both the fluidity and bleeding ratio were within the acceptable ranges.

It is considered that the clay contents of fine additives accounts for these testing trends well. Table 1 indicates the clay contents of B, FD, GS, and CP in a descending order. This order corresponds to their degree of influence on the flow values and bleeding rations, since the clay content is a key to water absorption capacity and consistency of fine additives, which influence the fluidity and bleeding characteristics of soil cement. The additives with the higher clay contents such as B and FD were able to control the bleeding ratio and maintain an appropriate fluidity.

**4.2 Unconfined compression strength**

UCS test results are shown in Figure 2. Overall, UCS increased with addition of fine additives, regardless of types of fine additive and mixing water. Among three recycled fine additives, GS had a highest improvement effect by combined use of the bentonite for SC = 150 kg/m³ cases, probably due to the gypsum hydration effects. The strength gain was almost equivalent to the cases in which 200 kg/m³ BC was applied with B and FD. Also, CP had a relatively higher improvement effect than FD even when the CP content was only 20 kg/m³.

There is no clear effect of seawater on the UCS of the soil cement amended by B and FD. However, the strength increased in the CP and GS cases when seawater was used as mixing water. Considering the chemical compositions of CP and GS, the strength gain by use of seawater may be attributed to the generation of hydrate products such as ettringite and friedel salts, which led to the densification on microstructures.

**4.3 Hydraulic conductivity**

Figure 3 shows the relationship between HC values and fine additive contents. Overall, HC values were equivalent to or lower than $1 \times 10^{-8}$ m/s, and decreased with an increasing fine additive content in all types of fine additives.

---

**Figure 1.** Flow values and bleeding ratios of the fresh soil cement affected by fine additive content: a) SC = 200 kg/m³, b) SC = 150 kg/m³ + B=20 kg/m³.

**Figure 2.** Relationships between fine additive content and unconfined compression strength: a) Bentonite (B), b) Foundry dust (FD), c) Concrete powder (CP) with B = 20 kg/m³, and d) Gypsum slag (GS) with B = 20 kg/m³.

**Figure 3.** Relationships between fine additive content and hydraulic conductivity: a) Bentonite (B), b) Foundry dust (FD), c) Concrete powder (CP) with B = 20 kg/m³, and d) Gypsum slag (GS) with B = 20 kg/m³.
In addition, HC values in the seawater cases were lower than those in the tap water cases. Particularly, for the cases of CP and GS, more than one order of magnitude lower HC values were achieved by using seawater. Adding GS combined with 20 kg/m³ bentonite achieved the lowest hydraulic conductivity close to $1 \times 10^{-11}$ m/s, which indicates an excellent hydraulic barrier performance. These results can also be explained by the densification effects, as indicated by the higher UCS.

Figure 4 shows the relationship between UCS and HC values for all the test cases. Apparently, HC values have a correlation with the UCS, and the HC values decreases with an increasing of UCS. However, HC values in the cases in which seawater was used are lower than those mixed with tap water for equivalent UCS. One potential mechanism is the densification effects observed for CP and GS, as mentioned above. Another potential mechanism related to B and SD cases is montmorillonite hydration behaviors affected by seawater. Figure 5 indicates the wet density of the specimen after 28 days aging for B and FD cases. When tap water was mixed, wet density values decreased with an increasing fine additive content, due to montmorillonite hydration. However, when seawater was mixed, wet density was getting larger, probably because hydration of montmorillonite was limited by seawater. This increasing wet density may lower the hydraulic conductivity since fine additives may act as fillers. However, further study is necessary to verify the effects of these potential mechanisms on the hydraulic conductivity as well as microstructures of the soil cement specimens.

![Figure 4. Relationship between unconfined compression strength and hydraulic conductivity](image1)

Figure 4. Relationship between unconfined compression strength and hydraulic conductivity

![Figure 5. Wet density of the specimen after 28 days ageing affected by B and FD contents.](image2)

Figure 5. Wet density of the specimen after 28 days ageing affected by B and FD contents.

5 CONCLUSIONS

This manuscript addresses the effects of three recycled fine additives including concrete powder, foundry dust, and gypsum slag on the engineering properties of the soil-cement mixtures containing these fine additives with various mixing proportions, to verify the applicability of these fine additives to soil cement diaphragm wall construction.

Although addition of these fine additives decreased the fluidity of soil-cement slurry, acceptable fresh soil cement properties were achieved for all types of additives by appropriate mixing design. Adding the appropriate amount of fine additives improved the unconfined compression strength and decreased the hydraulic conductivity of soil-cement mixture after 28 days aging. Furthermore, using seawater as mixing water can also improve the strength and hydraulic barrier performances of soil-cement mixture. These results verify the applicability of these recycled fine additives and seawater to soil-cement diaphragm wall construction.

REFERENCES

1) ASTM D5084 (2010): Standard Test Methods for Measurement of Hydraulic Conductivity of Saturated Porous Materials Using a Flexible Wall Permeameter, ASTM International, West Conshohocken, PA.
2) Katsumi, T., Kamon, M., Inui, T., and Araki, S. (2008): Hydraulic barrier performance of SMB cut-off wall constructed by the trench cutting and re-mixing deep wall method, GeoCongress 2008: Geotechnics of Waste Management and Remediation, GSP No.177, M.V. Khire et al. (eds.), ASCE, pp.628-635.
3) Katsumi, T., Watanabe, M., Suminaga, I., and Fukagawa, R. (2002): Effect of the mixing properties on hydraulic containment performance of soil-cement applied to cutoff wall, Journal of the Society of Material Science, Japan, Vol.51, No.1, pp.19-24 (in Japanese).
4) JGS 0511 (2009): Method for Unconfined Compression Test of Soils, Japanese Geotechnical Society, Tokyo.
5) JIS R 5201 (1997): Physical Testing Methods for Cement, Japanese Industrial Standards Committee, Tokyo.
6) JIS R 5211 (2009): Portland Blast-furnace Slag Cement, Japanese Industrial Standards Committee, Tokyo.
7) Yoshi, K., Kechavarzi, C., Sutherland, K., Ng, M., Soga, K., and Tedd, P. (2010): Laboratory and in situ tests for long-term hydraulic conductivity of a cement-bentonite cutoff wall, J. Geotech. Geoenviron. Eng., Vol.136, pp.562–572.
8) JSCE-F522 (1994): Test Method for Bleeding Ratio and Expansion Ratio of Grout Mortar for Prepacked Concrete (Polyethylene Bag Method), Japan Society of Civil Engineers, Tokyo.
9) Ruffing, D. and Evans, J. (2014): Case Study: Construction and in situ hydraulic conductivity evaluation of a deep soil-cement-bentonite cutoff wall, Geo-Congress 2014, GSP No.234-235, A.J. Puppal et al. (eds.), ASCE, pp.1836-1848.
10) Uchiyama, N. and Kuroda, Y. (2003): Effect of fine powder from concrete rubble on soil-cement properties, Proc. 38th JGS Annual Conference on Soil Mechanics and Geotechnical Engineering, Japanese Geotechnical Society, pp.641-642 (in Japanese).