Property of mixture of foam shield tunneling surplus excavation soil and steelmaking slag under water casting

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\section*{ABSTRACT}

A significant amount of foam shield tunneling surplus excavation soil, which contain a foaming agent and a blow off inhibitor, has been produced on shield tunneling construction. To utilize the surplus soil effectively for reclamtion of harbor areas, engineering properties of the mixture of the surplus soil and steelmaking slag, which is an industrial byproduct in steel manufacturing, have been studied. Issues regarding the putting of the mixture in water was studied in this study. Two types of water putting ways were investigated through small-sized laboratory model experiments. One way was to put from the bottom of a water tank; the other was to put from the water surface. Effects of the ways for configuration of the sedimented mixture, bearing capacity of the mixture and segregation of the mixtures were studied by the experiments. Results show that the configuration of the sedimented mixture and the steepest gradient are not affected by the putting ways. The maximum and average bearing capacities of the ground surface were larger when the mixture was put from the water tank bottom. The water turbidity was smaller when the mixture was put from the water tank bottom.

\textbf{Keywords}: steelmaking slag, composite soil, segregation

\section*{1 INTRODUCTION}

Owing the progress of the Tokyo Gaikan Project in recent years, many tunnels have been constructed using the foam shield tunneling method, which is a method to excavate a tunnel while injecting foam into the chamber (Shield Tunneling Association of Japan, accessed 2020). By using this method, large amounts of water and soil may be expelled vigorously when the gate of the screw conveyor was opened. This phenomenon is known as a “blow out.” A foaming agent and a blow off inhibitor are injected into the ground to prevent a blow out when this method is used. The environmental impact of the foaming agent and blow off inhibitor in soil will be reduced by biodegradation; however, this soil is not effectively used because this soil is classified as a construction surplus soil. To use resources effectively, this soil should be used with an extended application method (Research committee on tunneling surplus excavation soil of Tokyo Gaikan Project, 2015).

Steelmaking slag is produced as a byproduct in steel manufacturing. There are two kinds of steelmaking slags such as a converter steelmaking slag and an electric furnace steelmaking slag. A steelmaking slag has a self-solidification property by hydraulic reaction. The mixture of this slag and a dredged soil is used as a Calcia improved soil by utilizing this self-solidification property. Solidification mechanism of this material has been considered as the pozzolanic reaction between silica and alumina components in dredged soil and the calcium component in steelmaking slag (Coastal Development Institute of Technology, 2016).

Mechanical characteristics of the mixture of a steel making slag and a foam shield tunneling surplus excavation soil has been studied for accelerating the effective utilization of the surplus soil (Kakihara et al., 2018; Kakihara et al., 2019). Kakihara et al. (2019) concluded that unconfined compression strengths of the material with no bio-degraded foam agent and a blow off inhibitor were lower than those with biodegradation. Kakihara et al. (2019) also concluded the strength of the mixture was affected by the void ratio.

As the authors intended to use the mixture for the reclamtion material of port areas, issues regarding the
putting of the mixture into water is investigated in this study. Small-sized laboratory model experiments were conducted for two types of putting way to examine the segregation possibility of the material and the slope gradient of the sedimeted material.

2. UNCONFINED COMPRESSION STRENGTH OF SOIL MIXTURE WITH GROUND GRANULATED BLAST-FURNACE SLAG IN SHORT CURING DURATIONS

2.1 Experimental materials

The basic materials used were sand and steelmaking slag. The sand was Sakuki sand (maximum particle size was 2.00 mm; \( \rho_s = 2.73 \text{ g/cm}^3; D_{50} = 0.216 \text{ mm} \)). The steelmaking slag was a converter steelmaking slag without an aging treatment (particle size was 0.075–4.75 mm; \( \rho_s = 3.36 \text{ g/cm}^3; D_{50} = 1.467 \text{ mm} \)). Figure 1 shows the particle size accumulation curve of Sakuki sand and the steelmaking slag. In all cases, the sand and steelmaking slag were mixed in a particle volume ratio of 2:1, and a ground granulated blast-furnace slag (BS hereafter, specific surface area = 4340 \text{ cm}^2/\text{g}; \( \rho_s = 2.89 \text{ g/cm}^3 \)) was added. Artificial seawater was used as the pore water.

![Particle size accumulation curve](image)

Fig. 1. Particle size accumulation curve of Sakuki sand and steelmaking slag.

Table 1. Cases of unconfined compression tests.

| Case name | Ratio of sand and steelmakin g slag (% in volume) | Ground granulated blast-furnace slag (% in volume) | Water content ratio (%) | Dry density (g/cm³) |
|-----------|-----------------------------------------------|-----------------------------------------------|------------------------|-------------------|
| BS5       | 2:1                                           | 5                                             | 20.91                  | 1.76              |
| BS10      | 2:1                                           | 10                                            | 20.28                  | 1.80              |
| BS20      | 2:1                                           | 20                                            | 18.55                  | 1.87              |

2.2 Procedure to prepare specimens

The sand, steelmaking slag, and the prescribed ratio of BS were placed in a bowl and mixed. The ratio of the ground granulated blast-furnace slag presented in Table 1 was the particle volume ratio against the mixture of the sand and steelmaking slag. After mixing the solid materials, artificial seawater was mixed in. The mixture was placed in a plastic mold (diameter 5 cm) at a height of 10 cm with preventing material separation. A supernatant liquid appeared in every specimen after the placing the mixture to the mold. Subsequently, the plastic molds were sealed, and the soil mixture was cured in a thermostatic chamber (temperature 20 °C) during prescribed days such as 1, 3, and 7 days.

Table 1 lists cases of unconfined compression tests performed in this study.

2.3 Experimental procedure

The specimens were subjected to unconfined compression tests after the prescribed curing days. The unconfined compression tests were conducted based on JIS A 1216 (2001).

2.4 Results and discussion

Figure 2 shows the relationship between the curing duration and the unconfined compression strength \( q_u \). Unconfined compression strengths increased with increasing the ratio of the ground granulated blast-furnace slag or with increasing the curing duration.

![Unconfined compression strength](image)

Fig. 2. Relationship between unconfined compression strength and curing durations.

![Ratio of \( q_u \) on each curing duration](image)

Fig. 3. Relationship between ratio of \( q_u \) on each curing duration to the average \( q_u \) of BS5 on each curing duration (\( q_u/q_{u,BS5} \)) and the ratio of ground granulated blast-furnace slag.

To observe the difference of \( q_u \) by the ratio of the BS in the specimens, the ratio of \( q_u \) on each condition to the \( q_u \) of BS5 of the same curing duration (\( q_u/q_{u,BS5} \)) was calculated. Figure 3 shows the relationship...
between the BS content ratio and the ratio of $q_d/q_{d,BS \text{SS}}$ at the same curing duration. As shown in this figure, $q_d/q_{d,BS \text{SS}}$ of the case of BS10 were around 3 regardless of the curing duration and those of the case of BS20 were varied between 6 to 14, but there were no tendency on the change of the ratio according to curing duration.

3 EXPERIMENTS OF PUTTING THE MIXTURE INTO WATER

3.1 Experimental objective

The purpose of this series of experiments were to survey the issue on the mixture putting into the water, as this mixture was considered to be used for the reclamation of port area. Especially, the slope and the surface bearing capacity of the mixture put into water and the segregation of the material were investigated.

3.2 Experimental materials and procedure

The materials used are the same as in Section 2. They are shown in Section 2.1.

In all cases, the sand and steelmaking slag were mixed in a particle volume ratio of 2:1, and a 5% of a BS was added. Artificial seawater was used as the pore water. The water content of the soil was set to 15% when mixing. The volume of 5650 cm³ of the mixture was placed in a pipe at the target dry density of 1.41 g/cm³. This target dry density was smaller than that set in Section 2, because it was hard to put the mixture into water by the large target density such as used in Section 2. Then, artificial seawater was injected to the pipe until it pooled over the soil by approximately 1 cm for the mixture saturated.

Figure 4 shows the experimental setup. As shown, the water tank used was the length of 79 cm, the width of 58.5 cm, and the height of 50.2 cm. The water tank was filled with artificial seawater until the height of 45 cm. A turbidimeter was set at the height of 16 cm from the bottom at the corner of the water tank. Turbidity in the water box during putting the mixture was not uniform, but the authors wanted to know the tendency of the turbidity in the box. The authors considered the measured turbidity was only an index of it.

![Fig. 4. Experiment setup of putting the mixture into water.](image)

For the mixture putting way, two kinds of ways were used: putting from the water tank bottom and putting from the surface of the water. Figure 5 shows each putting way. As shown in Fig. 5(a), in the way of putting from the water tank bottom, the lower end of the pipe filled with the mixture was placed on the water tank bottom, and the mixture was put by lifting the pipe in approximately 5 seconds. As shown in Fig. 5(b), in the way of putting from the water surface, the lower end of the pipe was closed using a plastic board and placed at the height of the water surface; then, the mixture was put by sliding the plastic board. All the mixture was put into water in around 1 second.

![Fig. 5. Ways of putting the mixture into water.](image)

Two experimental cases were performed in each of the putting way. In one case, the mixture put was cured for 1 hour. In the other case, it was cured for 3 days. Table 2 shows the experimental cases conducted in this study.

| Case | Way of putting the mixture | Curing duration | Measurement items |
|------|---------------------------|-----------------|-------------------|
| Case 1 | From water tank bottom | 1 hour | Configuration of sedimented mixture. Bearing capacity of the. |
| Case 2 | From water tank bottom | 3 days | Configuration of sedimented mixture. Bearing capacity of the. |
| Case 3 | From water surface | 1 hour | Configuration of sedimented mixture. Bearing capacity of the. |
| Case 4 | From water surface | 3 days | Configuration of sedimented mixture. Bearing capacity of the. |

The measurement items were the sedimented mixture configuration, surface bearing capacities of the sedimented mixtures, turbidity of water, and particle size distributions in several parts of the sedimented mixtures. The heights of the sedimented mixture were measured using a plumb in a 3-cm interval grid to determine its configuration. The bearing capacities of the sedimented mixture surface was measured by stabbing it with a simple bearing capacity tester (capacity 995 kPa, base area 50.3 mm²) They were measured in a 6-cm-interval grid. Turbidity was measured using the turbidimeter (capacity 800.0 NTU, measurement error ±3% FS) placed at the corner in the artificial seawater. The particle size distributions were measured through sieving tests for samples from the sedimented mixtures. These samples were collected from near the highest point area of the sedimented mixtures.
mixtures from the top to the bottom and were separated into three in the height direction: UPPER, MIDDLE, and LOWER. The wet weight of each sample was approximately 250 g. In addition, one sample was collected from the edge of the sedimented mixture weighed approximately 200 g.

### 3.3 Results and discussion

Figure 6 shows overhead view of each sedimented mixture. Color bar shown in right side of each figure is height index. This figure was created based on the measured height of the each sedimented mixture supported by counter line drawing tool. From this figure, there seems to be smaller difference in the maximum height and spread of the sedimented mixtures in both putting ways. The slope from the sedimented edge to the top of it was relatively linear. Therefore, the ratios of the distance from the top of the ground to the ground edge on the surface direction to the maximum height of the ground were calculated. Table 3 shows the results.

The difference of the steepest gradient in each case was small and the gradients were approximately 1:2, except that of Case 1.

The volume of sedimented mixture was calculated by integrals of contours shown in Fig. 6. The dry density was calculated from the dry mass of the mixture put and the calculated volume of the sedimented mixture. The average water content ratio of the sedimented mixtures was calculated. Because of the difficulty of measuring water content and low accuracy of measured volume of sedimented mixture, difference of dry densities of sedimented mixtures was not discussed here.

| Table 3. Steepest gradient, of the sedimented mixture. |
|---|---|
| Case 1 | 1:1.88 |
| Case 2 | 1:2.11 |
| Case 3 | 1:2.11 |
| Case 4 | 1:2.12 |

Figure 7 shows the bearing capacities of the sedimented mixture surface for Cases 2 and 4. Color bar shown in the right of the figure shows the legend of the color. The position of the square showed the position where bearing capacities were measured, and
the numbers presented in the square represents the bearing capacity (kPa) at that point. In this figure, the bearing capacities of sedimented mixture surface of Case 2 were larger than those of Case 4.

Table 4 shows the maximum bearing capacity, average bearing capacity, and coefficient of variation of the bearing capacities. As shown, the maximum and average bearing capacities of the sedimented mixture surface for the way of putting from the water tank bottom were larger. Based on the results of statistical F-test, which is a method that it verifies whether a variable parameter of two samples is different or not, the average bearing capacities between two ways had a significant difference. This means that the bearing capacity of the sedimented mixture surface of putting from the water tank bottom is larger than that of putting from the water surface.

![Figure 7. Bearing capacities of the sedimented mixture surface in Cases 2 and 4. ( Broken lines and axes show positions of the box walls. Gray area is outside the box. )](image)

Table 4. Maximum bearing strength, average bearing strength, coefficient of variation of bearing strength in Cases 2 and 4.

|      | Case 2 | Case 3 | Case 4 |
|------|--------|--------|--------|
| Bearing capacity | 126.7 (kPa) | 62.1 (kPa) | 0.366 |
| Bearing capacity | 85.7 (kPa) | 42.1 (kPa) | 0.444 |

The results in Section 2 show that the ratio of BS affects the strength of the mixture; therefore, it appears that the bearing capacities of the sedimented surface was affected by the separation of BS.

Figure 8 shows the relationship between the turbidity of the artificial seawater on putting the mixture and the elapsed time. One NTU is the turbidity to melt 1 mg of formazine in 1 L of water. The turbidity of the artificial seawater (4.5 NTU) is shown by dotted line in this figure. Comparing the turbidities of Cases 1 and 2 with those of Cases 3 and 4, the turbidities of the former were lower than those of the latter. The maximum turbidity in the way of putting from the water surface was approximately 150 NTU; alternatively, the maximum turbidity in the way of putting from the water tank bottom was approximately 25 NTU. Hence, the material separation of the way of putting from the water surface was easier than that of putting from the water tank bottom, in which the maximum volume of material separation differed by approximately seven times. If 1 NTU is the turbidity to melt 1 mg of a fine fraction in the soil in 1 L of water, then based on the maximum turbidity of Case 3 (143 NTU), the maximum dry mass of the separated material will be approximately 30 g. The reason of the turbidity was assumed to be the floating of the particles less than 0.075 mm. It is noteworthy that 73% of the particles less than 0.075 mm in the mixture comprised of BS, and the remaining was the fine fraction of the sand. BS to be mixed in the mixture was segregated by approximately 8% of its mass.

![Figure 8. Relationship between turbidity of artificial seawater during the mixture putting and the elapsed time.](image)

Therefore, the dry mass content ratio of the BS in the sedimented mixture was estimated by sieving the samples from the sedimented mixture near the highest point and on the edge of the sedimented mixture. Samples from the mixture near the highest point were separated to three such as upper part, middle height part, and lower part. They were called Upper, Middle and Lower samples. In this estimation, the ratio of fine
particles of sand to the BS assumed to be unchanged from the materials mixed.

Figure 9 shows the result of these estimations. As a reference, the volume content rate of the BS when the materials were mixed (4.69%) is shown in this figure by the dotted line. As shown, the dry mass content rate of the BS of Upper in Case 3 was larger than those of others. Assuming the reason of turbidity was as mentioned above and assuming all the turbidities lied on the sedimentsed surface, the dry mass content rate of the ground granulated blast-furnace slag of Upper was approximately 6%. The estimated values of BS included in Upper on Case 3 was slightly higher. Meanwhile, the dry mass content rates of the BS in Case 1 were small variance in Upper, Middle, and Lower samples. In general, though all of the dry mass content rates of the ground granulated blast-furnace slag exceeded 4.69% for Cases 1 and 3, they were almost equivalent to the dry mass content rate of the original mixture. The turbidity for Case 3 increased significantly when the mixture was put, but the amount of turbidity was small compared to the total mass of BS. That is the reason that the dry mass ratio of BS in the sedimentsed mixture appeared almost unchanged in Cases 2 and 4; therefore, the difference in the dry mass ratio of BS did not affect the difference in the bearing capacity of the sedimentsed surface in Cases 2 and 4.

Fig. 9. Difference in dry mass content rate of BS in the sedimentsed mixture on each divided position for Cases 1 and 3.

4 CONCLUSIONS

In this study, issues regarding the putting of the mixture into water is investigated in this study. Small-sized laboratory model experiments were conducted for two types of putting way to examine the segregation possibility of the material and the slope gradient of the sedimentsed mixture. In addition, the shear strength of the mixture in a short curing time was investigated based on unconfined compression tests.

The shear strength of the mixture in a short curing time increased with the mixing ratio of the ground granulated blast-furnace slag. The rate of change of shear strength by the mixing ratio of the ground granulated blast-furnace slag was not affected by the short curing time.

In the small-sized laboratory model experiments conducted, two putting ways were employed. One way involved putting the mixture from the water tank bottom, whereas the other involved putting the mixture from the water surface.

The sedimentsed mixture configuration put in water and the steepest gradient were not affected by the putting way.

The maximum and average bearing capacities of the ground surface were larger for the way of putting from the water tank bottom.

In terms of segregation, the maximum turbidity of the way of putting from the water surface was approximately seven times larger than that of the way of putting from the water tank bottom. However, the segregation of ground granulated blast-furnace slag was approximately 8% at the maximum turbidity. Therefore, the way of putting the soil mixture exerted a negligible effect on the ratio of the soil mixture to ground granulated blast-furnace slag.

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