Laboratory tests and a full-scale embankment of the mixture of slag and fine-grained soil

Tests de laboratoire et un talus à pleine échelle du mélange des scories et des sols à grains fins

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ABSTRACT: In this study, compression and permeability tests of samples of steel slag and fine grained soil of a constant mixture, were done in order to study the hydraulic mechanical properties of steel slag and fine grained soil. A full-scale embankment made with the mixture of steel slag and fine-grained soil was constructed, and the effect of alkaline leaching water from the embankment caused by rain and deformation caused by traffic load including large trucks were also investigated. It is conducted that emb ankment constructed with a mixture of steel slag and fine-grained soil can be of practical use.

RÉSUMÉ : Dans cette étude, des essais de compression et de perméabilité d'échantillons de scories d'acier et de sols à grains fins d'un mélange constant ont été réalisés afin d'étudier les propriétés mécaniques hydrauliques des scories d'acier et des sols à grains fins. On a construit un talus à grande échelle constitué d'un mélange de scories d'acier et de sols à grain fin, et on a également étudié l'effet de l'eau de lessivage alcalin provenant du remblai causée par la pluie et la déformation causée par la charge de la circulation, y compris les gros camions. Il est réalisé que le remblai construit avec un mélange de scories d'acier et de sols à grain fin peut être utile.

KEYWORDS: steel slag mixed soil, compaction characteristics, pH.

1 INTRODUCTION

The Great East Japan Earthquake of 2011 caused severe, widespread damage to property and deprived the lives of many (Mori et al. 2014). Embankment damage has been occurring recently from record-breaking localized torrential rainfall, severe typhoons and major earthquakes (Okimura et al. 1999). The causes of embankment collapse include insufficient compaction of materials during construction, insufficient drainage and inappropriate choice of materials (i.e., those with a large ratio of fine fractions). These causes have been clarified by investigations in embankment collapses. Embankments are earth structures that are commonly used in road and railway construction and residential land development, and are an important social infrastructure. Despite their widespread use and importance, embankments are not yet sufficiently resistant to natural disasters. From the viewpoint of protecting private property and preserving infrastructure, there is a pressing need to develop disaster prevention technologies for residential land and road embankments.

The materials that have been used for embankments are natural sand and crushed stone. With decreases in the availability of high-quality natural resources, recycled materials have been increasingly used in construction. For example, cement-treated soil is created by mixing soil removed from construction sites that often contain a large ratio of fine fractions with cement to improve grading, and the resulting soil has been used as substitute material for natural sand and crushed stone. This study addresses the use of steel slag as a grading improvement material that can substitute for cement. Steel slag is generated in large quantities as a byproduct of iron and steel production. Steel slag has hydraulicity and high bearing capacity as a construction material. It has been used as a subgrade material in road construction. However, the use of steel slag requires attention regarding its components and properties, which differ, depending on the stage of steel production process from which the slag is generated. If slag with a potentially high environmental load is misused in earthworks, the slag may affect the surrounding environment.

The authors conducted unconfined compression and permeability tests on specimens created by mixing steel slag and construction waste soil in a specified ratio to produce "steel slag mixed soil", and examined the physical and mechanical characteristics of the mixture. The effect of improvements in grading and compaction on the strength and permeability of the steel slag mixed soil was investigated. Based on the above tests, the authors constructed a full-scale embankment using steel slag mixed soil. The deformation of the embankment under traffic load, such as of large trucks and the influence of alkaline leakage from the embankment to the surrounding environment after rainfall were examined. To make the embankment quake-resistant and to minimize the outflow of alkaline leakage from the soil material of the embankment, the authors explored the optimum mix ratio of steel slag and appropriate construction techniques.

2 PHYSICAL AND MECHANICAL PROPERTIES OF THE STEEL SLAG MIXED SOIL

2 .1 *Sample preparation*

The raw materials used in this study were two types of steel slag, which were from two different furnaces and were age processed (hereinafter: "steel slag A" and "steel slag B"), and construction waste soil from earthwork. The physical properties of the above three materials are shown in Table 1. The particle density of steel slag A and that of steel slag B were higher than that of construction waste soil (hereinafter: "Soil"). The difference in the particle densities between the two types of slag and the soil is thought to influence the maximum dry densities of the slag materials. The initial pH of the soil was 8.8 and those of steel slag A and steel slag B were 11.5 and 10.8, respectively, which are highly alkaline.

Figure 1 shows the grain size distribution curves of each raw material, the steel slag A mixed soil, and the steel slag B mixed soil, with a mix ratio of 50% in specific volume. From Fig. 1, the fine fraction content of the soil is 50% or higher, while the fine fraction content of the steel slag mixed soil is lower than that of the soil, from which can be understood from the fact that the ratio of sand fraction increased and the fine fraction content decreased when the steel slag was added. In addition, the grain size distribution curves of steel slag A and steel slag B do not differ much; however, when the slags were mixed with soil, the average grain diameter of the steel slag A mixed soil was 0.8mm, and that of the steel slag B mixed soil was 0.07mm. The average grain diameter of the steel slag A mixed soil was

Table 1. Physical properties of the three materials.

	Steel slag A	Steel slag B	Soil
Soil density, ρ_s (g/cm^3)	3.294	3.051	2.694
Water content, w (%)	5.2	11.6	30.9
Liquid limit, w_L (%)	NP	NP	38.4
Plastic limit, w_P (%)	NP	NP	31.0
pH (%)	11.3	10.8	8.8
Maximum dry density, $\rho_{d\ max}$ (g/cm^3)	2.32	1.85	1.41
Optimum water content, w_{opt} (%)	11.3	18.9	29.3

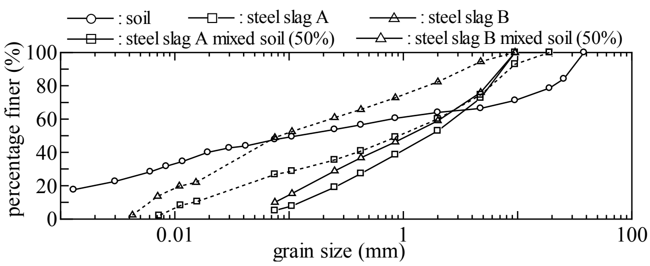

Figure 1. Grain size distribution curves.

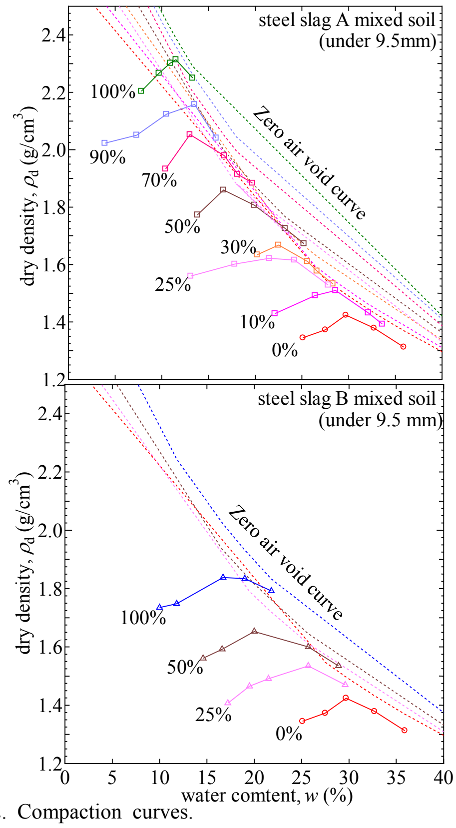

Figure 2. Compaction curves.

almost 10 times that of the steel slag B mixed soil. The mixed materials of steel slag and soil were created by mixing them on a volume ratio basis because of the great differences between the density of steel slag and that of soil.

2 .2 *Tests performed*

In the laboratory, a compaction test, an unconfined compression test and a permeability test were performed on the soil, steel slag A, steel slag B, steel slag A mixed with soil, and steel slag B mixed soil. The grain size of each specimen was adjusted to achieve a grain size of 9.5mm or smaller since the test specimens were small.

In the unconfined compression test, the specimens were formed in a plastic mold of 50mm in internal diameter and 100mm in height. The initial water content of each specimen was adjusted to the optimum water content based on the compaction curve of each material. The specimens were statically compacted in three layers by using a hydraulic jack (1Ec). The degrees of compaction of the specimens were 70% and 90%. After compaction, the specimens were wrapped in plastic film to maintain the water content during preparation. The specimens were then cured in ambient air for the specified period, and the influence of the number of days of curing on the specimens was examined. In the permeability test, the specimens were prepared by using containers that were 50mm in internal diameter and 50mm in height as a simplified permeability test apparatus. These specimens were formed and compacted as such that the initial water content was equal to the optimum water content. The specimens were statically compacted as one layer by using a hydraulic jack (1Ec). To investigate the changes in the coefficient of permeability, the specimens were examined after the specified period of water curing. Once the specimens had been water cured for the specified period, water was propelled through them for 24 hours using a vacuum pump. The permeability test was then conducted by using a falling head permeability test technique. The coefficient of permeability was determined in the test. The specimens of soil were prepared as such that the degree of compaction was 70%, 80% or 90%. The influence of the degree of compaction on the coefficient of permeability was examined.

2 .3 *Results and discussion*

Figure 2 shows the compaction curves of the steel slag mixed soil specimens that were prepared as such to have the specified mix ratios. The compaction curves for the two types of steel slag mixed soil indicate that the density of the soil increases with increase in mix ratio of the steel slag. The compaction curves distribute such that the lowest-content curve is at the bottom right corner and the curves are positioned farther up and left with each increase in content, which resulted partly from the decrease in the fine fraction content.

Figure 3 shows the relationship between the number of days of curing and the unconfined compressive strength for the steel slag A mixed soil. Increases in strength from those of steel slag A only is found in the steel slag A mixed soil; however, the magnitude of the strength increase varies depending on the mix ratio. The increase in strength of the specimen with a 50% mix ratio of steel slag tends to converge to the limit values at about 90 days of curing. When the variance in the degree of compaction is examined, increase in the strength after curing of a specimen with a low compaction of 70% can be seen. After curing, the specimen is strong enough to hold its shape without the mold. The curing contributes to the introduction of hydraulicity in the steel slag in the specimen.

Figure 4 shows the relationship between the ratio of steel slag in the soil specimen and the unconfined compressive strength of steel slag A mixed soil at 28 days of curing and at 60 days of curing. Regardless of the curing method, the unconfined compressive strength tends to be successively higher for each increment of slag content in the slag mixed soil up to 50% in mix ratio; however, the unconfined compressive strength tends to be successively lower in the steel slag mixed soil for each increment of mix ratio at and beyond 50%. The above phenomenon is estimated to be attributable to the water content of the specimen at preparation. In the unconfined compression test, the water content of the specimens at preparation was the optimum water content. However, the specimens differed in initial water content, because the optimum water content differed depending on the mix proportion ratio of the steel slag mixed soil (Fig. 2). For the material to develop strength, the specimen must have a water content that facilitates the hydration reaction, and it was suggested that the optimum water content of the steel slag mixed soil for that reaction during curing may coincide with the mix proportion ratio of 50% steel slag to 50% soil.

Figure 5 shows the relationship between the number of days of curing and the coefficient of permeability in the soil, steel slag A, steel slag B, steel slag A mixed soil (mix ratio of 50%), and steel slag B mixed soil (mix ratio of 50%). From the coefficients of permeability at the initial period of curing of the specimens, it is found that the soil has a coefficient of permeability of only 10^{-4}m/s, and both of the steel slags show higher coefficients of permeability than the soil shows. The two types of steel slag mixed soil have coefficients of permeability of 10^{-2}m/s to 10^{-3}m/s. The coefficient of permeability of steel slag, whose average grain diameter is greater than that of soil, is higher than that of soil immediately after curing. This analysis shows that the performance of the material possibly improves because of improved grading when steel slag is mixed with soil. The coefficient of permeability of the steel slag mixed soil is observed to slightly decrease with time after the 60th day of curing. This analysis suggests that, when the steel slag is mixed with the soil, the coefficient of permeability decreases with the development of hydraulicity in the steel slag during curing.

3 IN-SITU TESTS USE TO FULL-SCALE EMBANKMENT

3 .1 *Construction of the full-scale embankment*

Based on the results of laboratory tests, the test construction of an embankment was done as a step toward the practical use of slag mixed embankment materials. The in-situ tests investigated the deformation under heavy traffic load, such as that of large trucks, and the permeability of the constructed embankment.

The test embankment was constructed in three sections by using three types of materials: soil, steel slag A mixed soil, and steel slag B mixed soil. The mix ratio of steel slag for the two types of mixed materials was 25%. Each embankment section was 3.5m in length, 2m in height (the thickness of each leveled layer was 25cm; a total of 8 layers) and 4m in crown width. The slope gradient was 1:18. The three sections of the embankment were divided with wood planks. To measure the pH of the leakage, ditches were made at the embankment toe. Sloped approach roads of 70m long each were constructed using slag roadbed material before and after the road section constructed on the experimental embankment.

The embankment was constructed based on the Guideline for Road Earthworks, and 90% compaction was the target. Figure 6 shows the results of the in-site density test at completion of construction for each embankment section. For the embankment section constructed with soil only, over-compaction was feared, and roller compaction was used without vibration; however, vibration was employed for the third layer and above, because the resulting compaction up to the second layer did not satisfy the lower limit for specified compaction. The target degree of compaction was not attained even after increasing the number of roller compactions. Therefore, from the 5th layer on, the thickness of the layer for leveling and compaction was reduced to 12.5cm/layer, which is half of that of the lower layers. The 7th layer and higher layers were compacted by using dampers, because the embankment became too high for the vibrating roller to access the crown. The damper compaction was carefully done so to make the layers as dense as possible. The degree of compaction of the steel slag mixed soil (slag A and slag B) became low in the 4th layer. Compaction for the 4th layer and the layers above of steel slag mixed soil was done by increasing the number of rolling compactions. The strength of the embankment and the environmental load of alkaline leakage were investigated by conducting simple penetration tests and measurements of pH of leakage at specified intervals from immediately after construction completion to 6 months after the embankment road section was opened to large truck traffic.

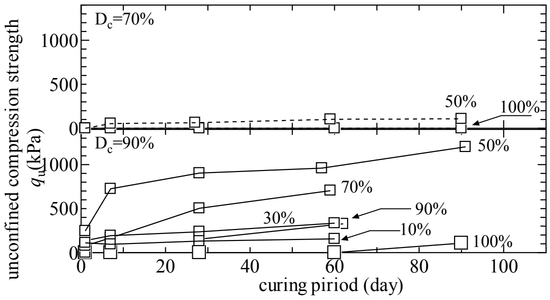

Figure 3. Relationship between the number of days of curing and the unconfined compressive strength of steel slag A mixed soil.

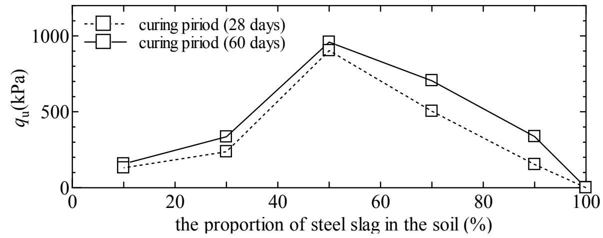

Figure 4. Relationship between the ratio of steel slag in the soil specimen and the unconfined compressive strength of steel slag A mixed soil.

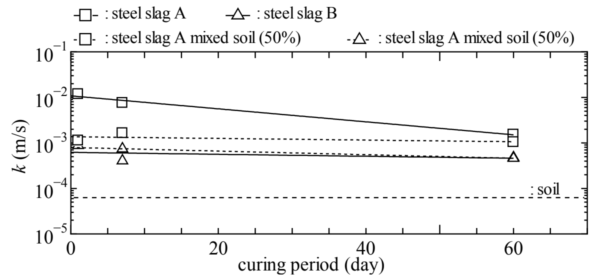

Figure 5. Relationship between the number of days of curing and the coefficient of permeability.

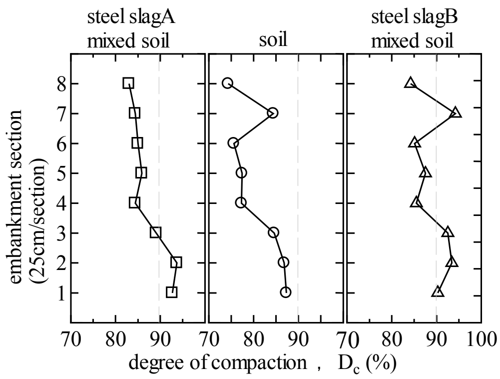

Figure 6. Results of the onsite density test at completion of construction for each embankment section.

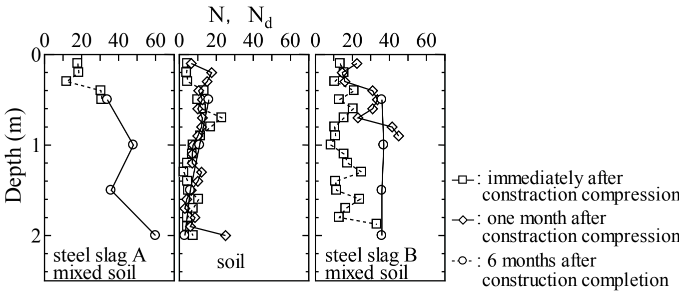

Figure 7. Results of the penetration tests.

Photo 1. Condition of the surface of the road section on the embankment.

3 .2 *Results and discussion*

Figure 7 shows the results of the penetration tests done at the crown of each embankment section. The figure shows curves for the results of simple penetration tests done immediately after construction completion and those done one month after the road section was opened to large truck traffic. The figure also shows the results of a standard penetration test done 6 months after the road was opened to traffic. For the embankment section constructed with soil only, the N-value ranged from 10 to 15 from immediately after construction completion to 6 months after construction completion. No increase in N-value with time was observed. For the embankment section constructed with steel slag B mixed soil, an increase in N-value was observed. The curing of the steel slag B in this section contributed to the increase in the N-value. In the embankment section with steel slag A mixed soil, N-values 6 months after completion were higher than those immediately after completion of construction. The result of the standard penetration test at the depth of 1m exceeded the N-value of 40. Photo 1 shows the condition of the surface of the road section on the embankment crown 2 weeks after the road section was opened to large truck traffic. The road surface of the section, which was constructed solely with soil, shows rutting and side-ways bulging of the crown. The surfaces of the road sections that were constructed with steel slag mixed soil showed no noticeable rutting or bulging in their crowns. From these findings, it can be concluded that the embankments constructed by using steel slag mixed soil have sufficient strength.

Figure 8 shows the pH values of water taken from the side ditches of the embankment. The side ditches were installed on the south and north sides of each embankment section, and covers were installed over the ditches to prevent rainwater from directly entering the ditches. Although there was one ditch on the south side of the embankment where a high value of pH was measured, the pH in general was around 9. The pH values measured 6 months after construction completion seemed stable. The broken lines in the figure show pH values for each of three materials at construction completion and those taken by boring at 6 months after construction completion. The specimens were taken from about 0.5m to 0.6m in depth inside the embankment. The lines show that the pH values of the specimens from the embankment section constructed with steel slag mixed soil are 11 or higher even 6 months after construction completion. The pH value of the water inside the embankment section constructed with soil only was about the same as that of the water in the side ditch at 6 months after construction completion. Based on the above pH measurements, it was found that very little rain water infiltrated into the embankment constructed with steel slag mixed soil, and that leakage did not flow out from the embankment. The water in the side ditches of the embankment was thought to be the rainwater that flowed over the slope of the embankment. The full-scale embankment experiment suggested that it was possible to prevent rainwater from infiltrating the embankment and to limit leakage outflow from the embankment to very low levels when a well-compacted embankment was constructed using steel slag mixed soil.

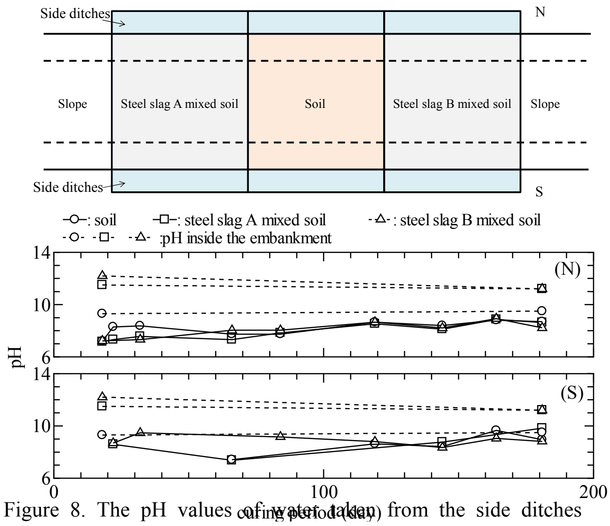

Figure 8. The pH values of water taken from the side ditches of the embankment.

4 CONCLUSION

In this study, the authors prepared specimens by mixing steel slag and soil in specified ratios, and examined the physical and mechanical characteristics of the steel slag mixed soil specimens. In addition, an embankment was constructed by using the steel slag mixed soil, and changes in the environmental load of alkaline leakgae with time were investigated. The following are the findings of this study.

1) The unconfined compression test revealed that there is a mix ratio of steel slag that achieves high strength.

2) When steel slag was mixed with soil, the permeability of the mixed material improved from grading improvements in the soil material, which resulted in improvements in the performance of the materials.

3) Based on the pH values of water pooled in the side ditches of the experimentally constructed embankment, it was verified that the leakage of highly alkaline water from inside the embankment can be controlled by sufficiently compacting the embankment.

5 REFERENCES

Mori T. Kazama M and Sato S. 2014. Seismic damage survey of large scale development housing sites in Sendai city due to The Great East Japan Earthquake. *Japanese Geotechnical Journal* 9(2), 233-253.

Okimura T., Niki M., Okamoto A. and Nanbu M. 1999.Investigation for Relationship between Damages to housing lots by the Hyogoken-Nambu Earthquake and various factors. *Journal of JSCE* Ⅳ-43(623), 259-270.