Proceedings of the 9ICEG
9th International Congress on Environmental Geotechnics
25-28 June, 2023 | Chania, Greece

https://doi.org/10.53243/ICEG2023-132

9ICEG

Application to construction material of coal fly ash and steelmaking slag–mixed material using premix method

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ABSTRACT

Investigation of effective utilization methods for steelmaking slag (SS) and coal ash (CA), the two major by-products of industrial waste in Japan, is an important issue in realizing sustainable development goals. Previously, each material has progressed in terms of its effective utilization. Hence, this study fabricates a new geomaterial that utilizes both by-products. Specifically, we fabricate a coal ash/SS-mixed material by mixing CA-mixed material with SS to strengthen the skeletal structure of the CA-mixed material, reduce the leaching of heavy metals from CA, and improve the California bearing ratio (CBR) and percentage of abrasion loss. We also attempt to use the new geomaterial as base course and embankment materials. Furthermore, experiments are conducted on the applicability of the fabricated material, a mixture of CA-mixed material and steelmaking slag, as geotechnical materials. The results show that the newly developed geomaterial exhibits the highest strength at a CA:SS ratio of 7:3. The results also show that usage of early-strength cement as a solidifier and setting the curing temperature at 50°C could improve the material strength before crushing. Finally, mixing CA-mixed materials with SS can improve the modified CBR and abrasion loss values, and thus, the fabricated material can be used as a safe upper base course material in geotechnical environment.

Keywords: Coal ash, Steelmaking slag, Mixed crush material, Premix, CBR, Leaching properties

1 INTRODUCTION

The establishment of Japan’s Act on the Promotion of Effective Utilization of Resources in 1991 provided a promising breakthrough for the effective use of steelmaking slag (SS), a byproduct of the steel production process. Approximately 14 million tons of SS are produced annually (Honda et al., 2016). Its unit weight and internal friction angle are larger than those of natural sand; thus, it can serve as an alternative material for natural stone and sand (Zore et al., 2010). Because of such material characteristics, SS is used for road or construction materials in Japan (Ichihara et al., 2010). There are several studies involving the application of SS in civil engineering materials, and its effectiveness has also been confirmed (Oshino and Kikuchi et al.,2021, Horii et al., 2013).

Conversely, coal is an essential fuel material used in electricity generation worldwide. Coal-fired power plants currently contribute 38% of global electricity, with some countries having a higher percentage (World Coal Association, 2020). According to the global coal ash (CA) production and utilization records (Anjani et al., 2019), effective CA utilization is only 1/4th of the total production. The top producers, India and China, have less than a 50% CA utilization level; however, Denmark, Italy, and the Netherlands have a 100% CA utilization level (Arpita et al., 2019). Although the effective utilization level in Japan is as high as 96.3%, cement utilization largely affects this percentage, and its effective use in civil engineering has not progressed significantly. Therefore, Japan Coal Energy Centre (JCOAL) published an article on “Effective Use Guidelines for Coal Ash Mixture (edited by Port Construction)” to increase the use of CA generated in the civil engineering field (JCOAL 2011, JCOAL 2014, JCOAL 2015). Although the publication of these guidelines has increased the use of CA composites, there is a need for further application guidelines due to the increasing production of CA. CA-mixed materials, which are primarily derived from CA, have been studied because of their material properties, long-term durability, environmental safety, and their usefulness as civil engineering materials (Sato and Fujikawa,2015, Sato, Fujikawa and Koga 2015). In addition, the Japan Society of Civil Engineers (JSCE) has published technical guidelines (JSCE, 2021) for the effective use of CA, and its effective use as a civil engineering material is progressing. However, crushed CA-mixed materials have low abrasion resistance as upper base course materials for pavement, and there are concerns about the leaching of heavy metals derived from CA.

Thus, we fabricate a crushed CA/SS-mixed material using a premixing method, where SS with high particle strength is mixed with CA during crushed material production. We also present the findings of our study on the effect of the fabricated material on the suppression of heavy metal leaching.

2 MATERIALS FOR EXPERIMENT

CA from thermal power plants and SS from steel mills were used in this experiment. The SS was steam aged while considering material expansibility. Figure 1 depicts the particle size distribution curve, and Table 1 lists the physical properties. Blast furnace cement class B (hereinafter BB), early-strength Portland cement (hereafter H), and slaked lime were used as solidifiers to produce CA/SS mixtures. Figure 2 depicts the production process of crushed CA/SS-mixed materials, which was done at the plant. Each sample was mixed in the proportions shown in Table 2 and heated and humidified at 50°C for 48 h. The material is then crushed and used after 28 days of particle size adjustment. Here the grain size adjustment of the crushed material is based on the median of the grain size range of base course materials in Japan.

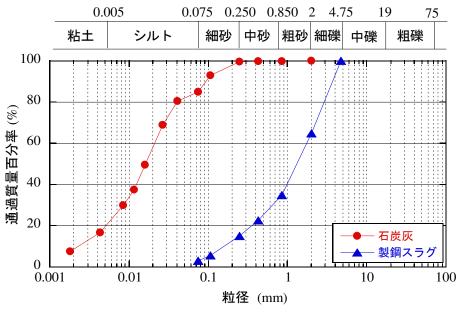


Figure 1. Particle size distribution curve

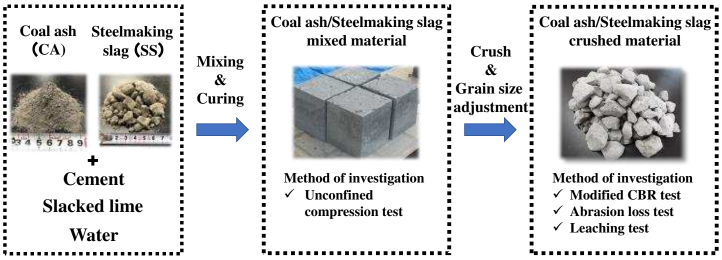


Figure 2. Production process of CA/SS-mixed and -crushed material

3 STRENGTH PROPERTIES OF COAL ASH/STEELMAKING SLAG-MIXED MATERIALS

In this study, the strength of the CA/SS-mixed materials before crushing is evaluated in terms of unconfined compressive strength to improve their quality after crushing.

Table 1. Physical properties of CA and SS

Sample	Particle density ρ_s (Mg/m^3)	Natural water content w_0 (%)	Fine grain content Fc (%)
CA	2.188	0.5	85.0
SS	3.536	1.8	1.2

Table 2. *Mixing conditions of CA/SS-mixed material*

CA :SS	CA (%)	SS (%)	Cement※1 (%)	Water※2 (%)	Slacked lime (%)
10:0	100	0	25	24.2	3
9:1	90	10			
8:2	80	20			
7:3	70	30			

※1Cement and slacked lime content by mass of coal ash and steel slag

※2Water addition ratio by mass of coal ash, steel slag and slacked lime

3.1 Testing procedure

Table 3 lists the experimental conditions for the effects of different mixing ratios of SS, and Table 4 lists the experimental conditions for the effects of different curing temperatures. In this experiment, SS was used as a part of CA. In this experiment, SS with a particle size of 4.75 mm or less was mixed with 10%–30% of CA, considering that SS is used as a part of CA.
The samples were mixed according to the mixing conditions in Table 2 and stirred with a Hobart mixer. After mixing, the sample was placed in a PVC mold with a diameter of 5 cm and a height of 10 cm, and 3 layers were pushed and compacted 12 times to 1Ec using a 1.5-kg rammer.

Table 3. *Experimental conditions for the effects of different mixing ratios of SS*

Cement	Mixing ratio CA :SS	Curing method	Curing day t (day)
BB H	10:0 9:1 8:2 7:3	Method A	2 7 28

Table 4. *Experimental conditions for the effects of different curing temperatures*

Cement	Mixing ratio CA :SS	Curing method	Curing day t (day)
BB H	10:0 7:3	Method A Method B	2 7 28

Currently, CA-mixed materials are prepared at heating and humidifying curing temperatures of 50°C–60°C to promote cement hydration and early-strength development through high-temperature curing. Therefore, after demolding, Method A was performed: air curing after heating and humidifying at 90% humidity for 2 days according to the curing conditions shown in Figure 3. In addition, to investigate the effect of curing temperature on compressive strength, a curing temperature of 20°C was investigated for CA:SS ratios of 10:0 and 7:3 (Method B). After heating, humidifying, and curing in air, the specimens were cured at a constant temperature of 20°C for a specified number of curing days, and then unconfined compression tests (JIS A 1211) were conducted.

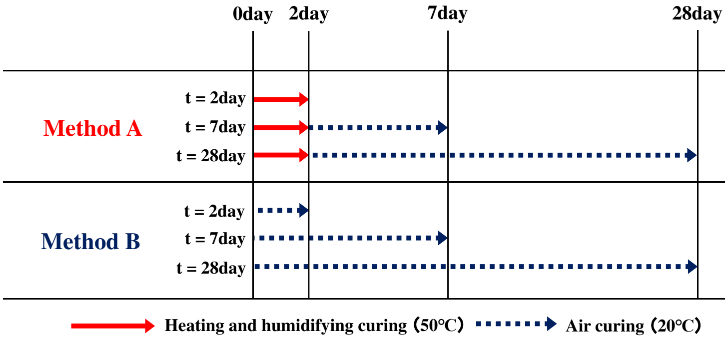


Figure 3. *Curing conditions of Methods A and B*

3.2 Effect of the mixing ratio of steelmaking slag

Figures 4(a) and (b) show the experimental results of unconfined compressive strength and the number of curing days for different types of cement stabilizers. From the figures, regardless of the number of curing days and type of cement stabilizer, the strength increases when SS is mixed with CA (maximum for CA:SS = 7:3) compared to using only CA (CA:SS = 10:0).

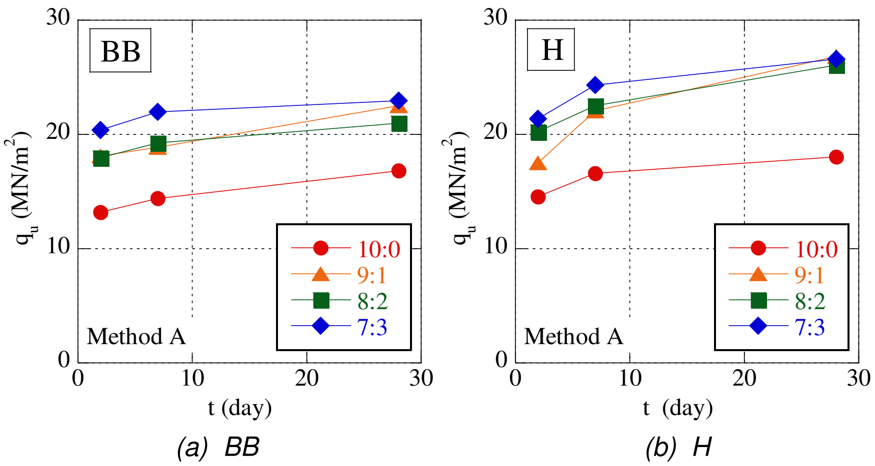


Figure 4. *Results of unconfined compressive strength and the number of curing days*

This is thought to be due to the solidification effect of the latent hydraulic property of SS, as well as the effect of increasing the particle size of the mixed material by mixing with SS, which has a larger particle diameter than CA. The strength of the mixture of exceeded 20 MN/m^2 after 2 days of curing, regardless of the mixing ratio, indicating that the mixture has sufficient strength as a solidified material before crushing.

In other mixing ratios, the strength was not as high as CA:SS = 7:3 after 2 days of curing. However, after 28 days of curing, the strength of all mixtures was equivalent to that of CA:SS = 7:3, regardless of the type of solidifier used. Therefore, it is considered that a high-strength mixed material can be produced by ensuring a sufficient curing period after crushing.

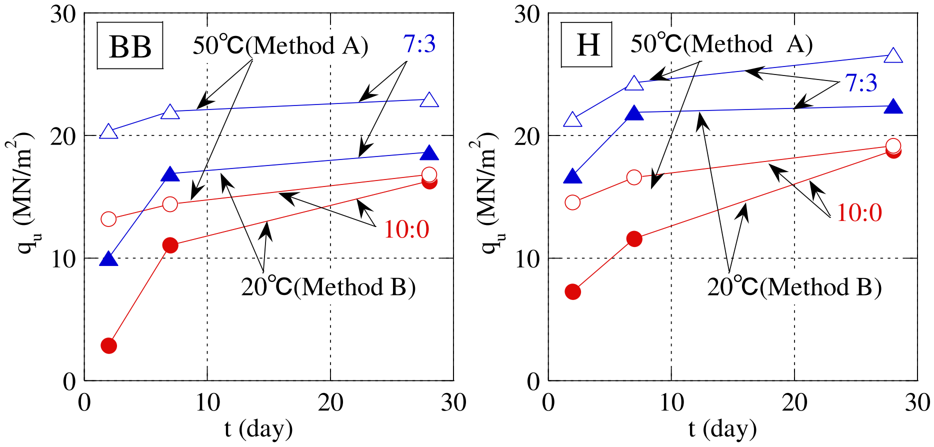
In terms of solidifiers, H exhibits larger values than BB irrespective of curing days, exceeding 20 MN/m^2 under almost all conditions. This is due to the higher content of aelite (C_3S) among the cement constituent compounds in H and its larger specific surface area, resulting in rapid hardening and higher initial strength development (Benson et al., 2020).
These results indicate that the strength of the CA/SS mixture tends to increase as the proportion of SS in the mixture increases. In addition, the highest strength was obtained at CA:SS of 7:3 under the present

mixing conditions. Although the strength increases as the slag content increases, this condition was set as the limit in this study because the purpose of this study is to effectively utilize CA.

3.3 Effect of Different Curing Temperatures

Figures 5 (a) and (b) show the results of unconfined compressive strength and the number of curing days for different solidification materials. In this study, two conditions were examined: CA:SS = 7:3, which produced the highest strength in terms of mixing ratio, and CA:SS = 10:0 (CA alone) as a comparison.

According to the experimental results on the effect of curing temperature on unconfined compressive strength, superior strength development occurs from the initial curing period at a higher curing temperature of 50°C, regardless of the solidification materials and mixing conditions (Zhang et al., 2014). The strength of the material also tends to increase with the number of curing days.



(a) BB *(b) H*

***Figure 5.** Results of unconfined compressive strength and the number of curing days*

4 PERFORMANCE EVALUATION OF CRUSHED COAL ASH/STEELMAKING SLAG-MIXED MATERIAL AS UPPER BASE COURSE MATERIAL

4.1 Testing procedure

In this study, a modified California bearing ratio (CBR) test (JIS A 1211) and an abrasion loss test (JIS A 1121) of coarse aggregates were conducted to evaluate the performance of the fabricated material as a base course material. Two mixing conditions, CA:SS=7:3 and CA:SS=10:0, were used in the experiments for comparing. In addition, crushed CA-mixed materials produced in 2018 and 2020 were also used to investigate the difference in ash type. Table 5 shows the experimental conditions for the modified CBR test. Each layer of the specimens was subjected to 17, 42, and 92 times of compaction, after adjusting the moisture content of the specimens according to the optimum moisture content obtained using the E-b method. The modified CBR values were then obtained from the water absorption expansion and penetration tests.

Table 5. *Experimental conditions for the modified CBR test*

CA :SS	Water content	Compaction times
10:0 (2018)	Optimum	17
10:0 (2020)		42
7:3 (2020)		92

For the coarse aggregate abrasion loss test (JIS A 1121), the specimens and 12 steel balls were placed in a Los Angeles testing machine, and after 500 revolutions of the machine at 30–33 times per minute, the abrasion loss was calculated from the residual mass on a 1.7-mm sieve.

To evaluate the safety of the crushed material in a geotechnical environment, the crushed material adjusted to a particle size range of recycled base course materials was tested (JIS K 0058-1). In the experiment, pure water, at a pH 5.8–6.3, was mixed at a liquid–solid ratio of 10, and the mixed solution was stirred with propeller agitation (200 rpm) for 6 h and later filtered to prepare a test liquid.

4.2 Performance evaluation of fabricated material as upper base course material

Figure 6 shows the modified CBR test results, and Figure 7 shows the modified CBR values at 95% degree of compaction. The particle density of SS is larger than that of CA, indicating that the maximum dry density in the compaction test also increased after mixing with SS. All modified CBR values of the 2020 crushed material (CA:SS = 10:0) at 95% compaction met the criteria for upper base course materials, regardless of the SS mixing ratio. However, the 2018 material (CA:SS = 10:0) did not meet the criteria for upper base course materials, indicating that different ash types have a significant effect on the modified CBR values.

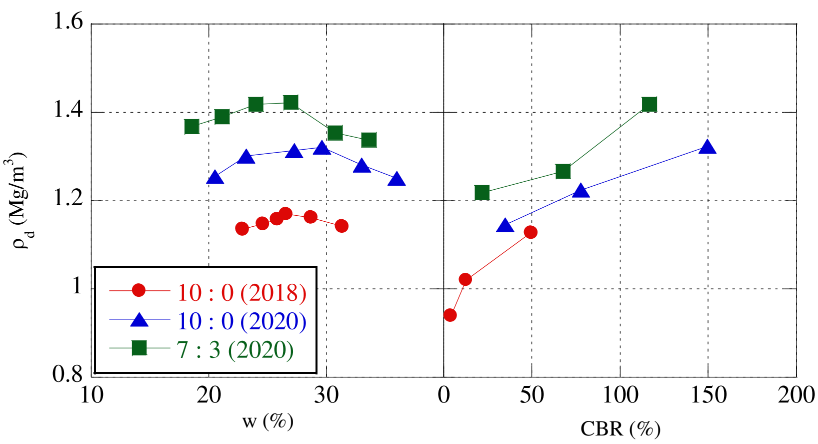


Figure 6. *Modified CBR test results*

Figure 8 shows the abrasion loss test results, showing that all conditions satisfied the specified values for upper base course materials and that the addition of SS to the mixture significantly improved the abrasion loss. This is thought to be due to the solidification effect of the hydraulicity of SS, as well as the effect of increasing the particle size of the crushed material by mixing with SS, which has a larger particle diameter than CA.

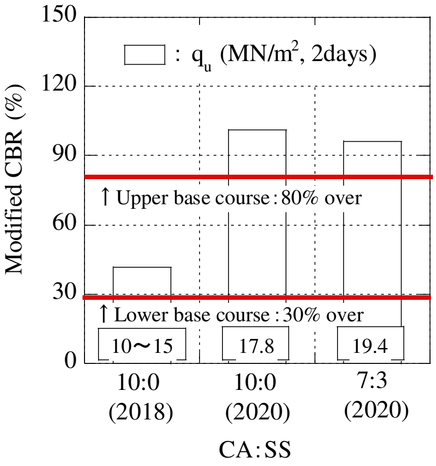


Figure 7. *Modified CBR values at 95% degree of compaction*

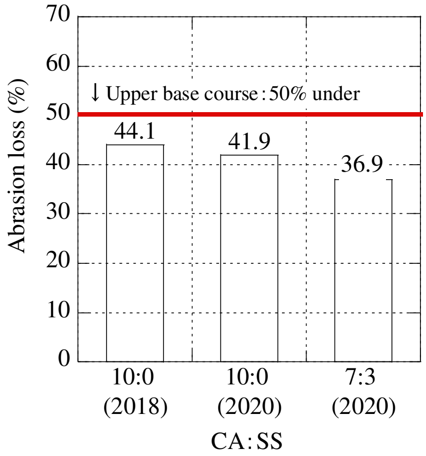


Figure 8. *Results of abrasion loss test*

Table 6. *Environmental safety evaluation of the CA/SS mixture*

Sample	pH	Leaching concentration [mg/L]			
		Cd	Pb	Cr(VI)	B
10 : 0 (2018)	11.0	N.D.	N.D.	N.D.	0.12
10 : 0 (2020)	11.5	N.D.	N.D.	0.01	0.07
7 : 3 (2020)	11.5	N.D.	N.D.	N.D.	0.08
Soil environmental standard (JP)		0.003	0.01	0.05	1

Table 6 shows the environmental safety evaluation of the CA/SS mixture. Under all conditions, although a slight leaching of boron was observed, all results satisfied the soil environmental standard values. Although the pH value exceeded 11, the diffusion of alkali components that permeated into the surrounding ground was suppressed by the buffering action of the soil (Sakate 1987). Therefore, the influence of CA/SS mixture on the surrounding ground when used as a base course material is low.

5 CONCLUSIONS

1) Premixing SS with CA-mixed material improves the strength of the material before crushing, and the highest strength was found at CA:SS = 7:3. It was also demonstrated that the material strength before crushing could be increased using early-strength cement and setting the curing temperature to 50°C.

2) It was found that the premix crushed CA-mixed material can be used as a safe upper base course material in geotechnical environments because the modified CBR and abrasion loss values can be increased by mixing with SS.

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