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Strength characteristics of ground improved using high-blast-furnace-slag-content cement

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ABSTRACT: Reducing CO_2 emissions is critical for addressing global climate change. In Japan, the CO_2 emissions from cement production constitute approximately 4% of the country's total CO_2 emissions. This study investigated a technological system designed to significantly reduce CO_2 emissions during cement production. The system involves the development of high-blast-furnace-slag-content cement and its application in concrete structures and ground improvement. In this study, high-slag-content cement with a slag content of >60% was used. The composition of the high-slag-content cement was determined based on laboratory strength tests of artificial ground by varying the mixture of blast-furnace slag and gypsum, which acted as a reaction accelerator for the blast-furnace slag. Next, the high-slag-content cement was applied for in situ ground improvement in several coastal areas in Japan. Prior to in situ construction, laboratory mix design tests were performed to confirm the compressive strengths of the soils extracted from the construction sites. The compressive strength and elution of hexavalent chromium were investigated in situ. The results showed that the high-slag-content cement could reduce CO_2 emissions during production by 65% and 45% compared to ordinary Portland cement and conventional Type-B blast-furnace cement, respectively. The compressive strength of the high-slag-content cement was comparable to that of Type-B blast-furnace cement, and the elution of hexavalent chromium was lower than 0.05 mg/L. In addition, the coefficients of variation in unconfined compressive strength and the ratios of the in situ field strength to laboratory compressive strengths satisfied the target value. On the basis of the laboratory and in situ test results, high-slag-content cement is suitable for ground improvement. The developed high-slag-content cement is recommended for practical applications, considering that it satisfies design strength requirements, and its production leads to reduced CO_2 emissions compared to conventional cement production.

KEYWORDS: Ground improvement, CO_2 emissions, blast-furnace slag, compressive strength, hexavalent chromium.

1 INTRODUCTION

Although the total CO_2 emissions in Japan have been decreasing in recent years (JCCCA, 2021), they reached 1.04 billion tons in 2020, making CO_2 emission reduction a significant challenge for preventing global warming. Approximately 4% of CO_2 emissions in Japan occur during cement production. In 2020, the total cement production was 55.7 million tons, of which approximately 29.4 and 7.8 million tons were used for concrete and ground improvement, respectively (JCA, 2021). Therefore, if the CO_2 emitted during cement production for ground improvement is reduced, this can contribute to decreasing the total CO_2 emissions in Japan.

Using cement mixed with blast-furnace slag (BFS) effectively decreases CO_2 emissions during cement manufacturing (Sakai and Daimon, 2007). In Japanese JIS standards, blast-furnace cement is classified as Types A, B, and C, depending on the proportion of BFS, and Type-B blast-furnace (BB) cement contains 40%–60% BFS. In Japan, BB cement containing approximately 40% BFS is widely used for ground improvement.

Our research group has been conducting research on high-slag-content cement containing >60% BFS to reduce the amount of CO_2 emitted during cement production (Yonezawa et al., 2013). The aim is to minimize CO_2 emissions by replacing Portland cement and BB cement with high-slag-content cement. The application of high-slag-content cement in high-strength reinforced concrete (Tsuji et al., 2014), civil-engineered concrete (Hashimoto et al., 2014), cast-in-place concrete piles (Ogawa et al., 2014), and ground improvements (Kono et al., 2010) has been considered.

This paper describes the composition of high-BFS-content cement suitable for concrete and ground improvement. In particular, laboratory test results on the proportion of BFS and the amount of gypsum added as a reaction promoter to ensure the strength of ground improvement are presented. Furthermore, the strength characteristics of the ground improvement constructed in situ on soft ground in the coastal areas of Japan were investigated and compared with those of BB cement to verify the applicability of the newly developed high-slag-content cement for ground improvement.

2 COMPOSITION AND EFFECTS OF HIGH-SLAG-CONTENT CEMENT

2.1 *Overview of tests*

The required performance of cement used in ground improvement includes achieving the necessary strength after a specified curing period (curing after 28 or 91 days) and ensuring that hexavalent chromium elution is below the environmental standard (MOE, 1991). Furthermore, during in situ construction, the stability of construction machinery on already improved ground should be ensured, and strength equal to or higher than that of the original ground is required, even immediately after improvement (curing after 1 or 3 days). In this study, the target strength and hexavalent chromium elution were set as follows: 28- and 91-day curing strengths for ground improvement using high-slag-content cement equivalent to BB cement, and 1- and 3-day curing strengths for ground improvement using high-slag-content cement equivalent to the original ground.

Yonezawa et al. (2013) conducted compressive strength tests on mortars made of mixtures of BFS and anhydrite by varying the ordinary Portland cement (OPC) content (Fig. 1). They demonstrated that high strength was achieved when the OPC ratio was 1% or lower, or higher than 20%. In this experiment and the mass ratio of BFS to anhydrite gypsum (CS) was set to 85:15.

2.2 *Materials*

Table 1 lists the chemical compositions of the materials used to produce the high-slag-content cement. In this test, BFS without SO_3 was used. Artificial ground samples with a water content of 18% were prepared by mixing silica sand and Gairome clay at a mass ratio of 9:1.

2.3 *Effect of OPC content ratio*

Figure 2 shows the relationship between the compressive strength of the improved soil and the OPC content after 7, 28, and 91 d of curing. The percentage contents of OPC to binder (a mixture of BFS, CS, and OPC) were set to 1%, 3%, 5%, 10%, 15%, 20%, 25%, 30%, and 35%, based on Yonezawa et al. (2013). The CS content was set to 5%. The binder content was 200 kg/m³, and the binder-to-water ratio was 80%.

Except for the 1% OPC content and 7-day curing conditions, the strength of the ground improvement using high-slag-content cement was higher than that using BB cement. In addition, for the 1% OPC content, the strengths at 28 and 91 d of curing became greater than or comparable to those under other conditions although the strength at 7 days of curing was lower. When the OPC content ratio was 1%, the BFS reacted, and strength increased; however, when the OPC content ratio increased to 3%–15%, the strength decreased. A small amount of added OPC (1%) possibly acts as a catalyst to activate the hydration reaction of BFS, whereas larger amounts no longer function effectively as a catalyst. This mechanism is unclear, but hydrates are likely to be formed on the BFS surface with increasing OPC content, inhibiting BFS hydration (Harada et al. 2023). When the OPC content ratio was 20%–35%, the experimental results showed similar strength values.

Considering the practical application of concrete or ground improvement, it is challenging to control the OPC content at a trace level of 1% or smaller, and because a relatively stable strength develops when the OPC content ratio is approximately 20%–35%, the OPC content ratio was set to 30%.

2.4 *Effect of anhydrous gypsum*

Figure 3 shows the relationship between the compressive strength of the improved soil and the amount of CS at curing periods of 1, 3, 7, 28, and 91 days. For the tests, the proportion of OPC was set to 30%, and the proportion of CS in the binder (a mixture of BFS, OPC, and CS) ranged from 0.7% to 16.4% (1%–10% in terms of the SO_3 content).

By setting the CS ratio to 2.5% or higher, the strength required for heavy machinery operations after 1 day of curing (q_u = 0.2 N/mm²; JCA, 2025) could be achieved, and the strength exceeded that of BB cement. The strength for up to 7 days of curing tended to increase as the CS content increased. However, the strength at 28 and 91 days tended to remain unchanged or decrease when the CS content ratio was 5% or higher. This is attributed to the excessive addition of gypsum, which reduces the hydration reaction of the BFS. Based on these findings, a CS content of approximately 5% is appropriate when the OPC content is 30%.

2.5 *Composition of high-slag-content cement*

Figure 4 shows the high-slag-content cement composition suitable for ground improvement. Based on the test results for cement paste reported by Yonezawa et al. (2013) and the improved soil, the OPC and CS content ratios were set to 30% and 5%, respectively. If only the ground improvement test results were considered, it would be possible to set the OPC content ratio at approximately 20%; however, considering that the intention was to also use it for concrete, the OPC percentage was set at 30%.

High-slag-content cement may reduce CO_2 emissions by 45% compared to BB cement (JSCE, 2005), and up to 65% compared to OPC (JSCE, 2005). The CO_2 emissions of the CS were assumed to be similar to those of limestone powder because the process of crushing and classifying natural ore is similar to the manufacturing process of limestone powder. The CO_2 emissions shown in Figure 4 only reflect the CO_2 emissions contained in the raw materials and those generated during production; however, they exclude CO_2 emissions required for transporting materials.

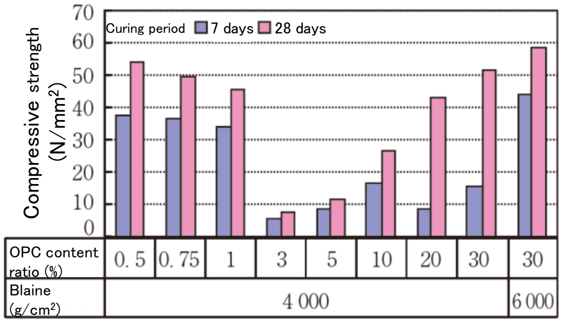

Figure 1. Effects of OPC content ratio on the compressive strength of cement paste (Yonezawa et al., 2013).

Table 1. Chemical compositions of materials.

Material	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3
BFS	34.17	13.79	0.30	43.97	5.38	-
OPC	21.41	4.84	3.20	65.01	1.08	2.02
CS	1.57	0.49	0.10	39.40	0.20	57.47
BB	–	–	–	–	3.23	1.93
Silica sand	94.30	2.20	1.20	-	-	-
Gairome clay	48.13	34.51	1.36	0.20	0.24	-

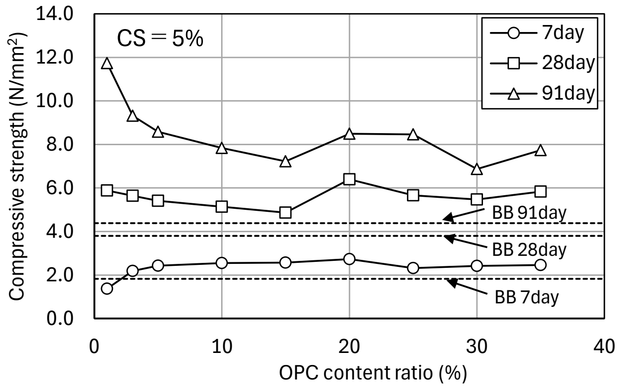

Figure 2. Effects of the OPC content ratio on the compressive strength of improved soil.

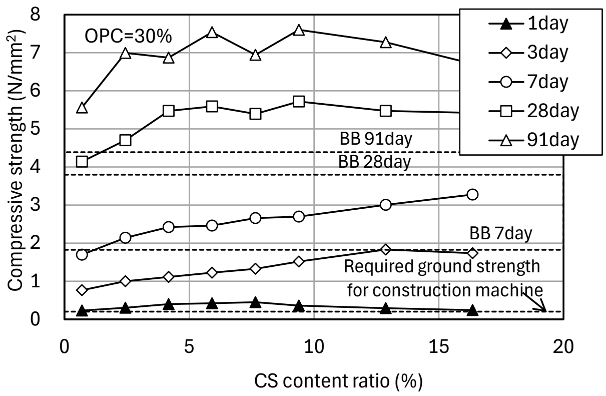

Figure 3. Effects of the CS content ratio on the compressive strength of improved soil.

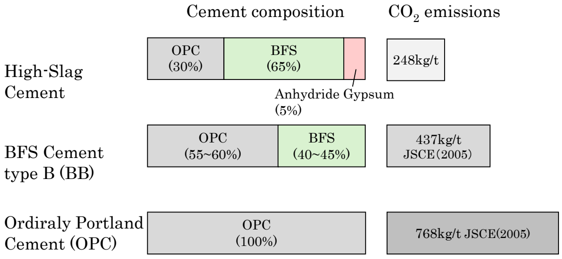

Figure 4. Cement composition and CO_2 emissions.

3 STRENGTH CHARACTERISTICS OF GROUND IMPROVED USING HIGH-SLAG-CONTENT CEMENT

3.1 *Outline of laboratory tests and in-situ construction test*

Ground improvement was performed in-situ using practical construction equipment, and quality investigations, including strength, were conducted to verify the applicability of high-slag-content cement for ground improvement. The construction was conducted on soft sandy ground in the coastal areas of Osaka, Tokushima (Kono et al., 2018), and Fukuoka (Nagamatsu et al., 2018).

The tests included preliminary laboratory strength tests using soil samples collected from the site, and strength tests using core sample specimens collected after constructing the ground improvement. In the tests using core sample specimens, the average strength of the cores, variation in core strength, and the ratio to laboratory strength were investigated. Additionally, tests were conducted simultaneously in both laboratory and field settings using BB cement to compare their strengths.

3.2 *Materials, ground conditions, and test conditions*

Table 2 lists the chemical compositions of the high-slag-content and BB cements. High-slag-content and BB cements were used as binders in three in situ construction tests. The ratio of the BFS, OPC, and CS in the cement with a high BFS content was 65:30:5.

Figure 5 shows the soil profile of the ground targeted for improvement, and Table 3 lists the properties of the soil to be improved. Soft sand ground, which has the potential for liquefaction during earthquakes, was targeted for improvement. At the Fukuoka site, the fill layer above the soft sand layer was also targeted for improvement.

Table 2. Chemical compositions of materials.

Material	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3
High-slag-content cement	28.21	10.62	1.05	49.95	4.12	4.02
BB cement	–	–	–	–	3.23	1.93

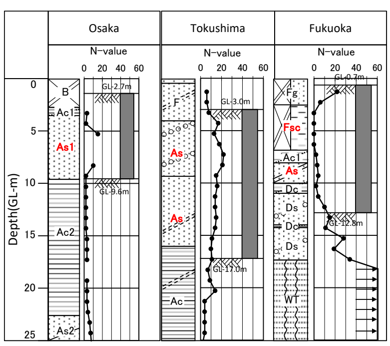

Figure 5. Soil profiles of in situ construction sites.

Table 3. Soil properties determined in situ at construction sites.

Construction site and soil type		Wet density (g/cm^3)	Water content (%)	Grain size (%) Clay	Silt	Sand	Gravel
Osaka	As1	1.89	29.7	13.0	24.5	61.7	0.8
Tokushima	As	2.04	20.4	7.7	19.2	59.0	14.1
Fukuoka	Fsc	1.66	55.5	43.7	53.1	3.2	0.0
	As	1.78	32.8	10.8	16.6	66.1	6.5

3.3 *Laboratory-mixed test results*

Table 4 lists the design strength of the in situ ground improvement and the conditions of the laboratory mixing test used to determine the mixture proportions for ground improvement at the construction site. Furthermore, because the design strength was relatively high (1.8–2.1 N/mm²), the water–cement ratio (W/C) of the cement slurry was set to 70%–80%. Soil samples collected at the site were used for the laboratory mixing test, and the unconfined compressive strength was measured after 28 days of curing.

Figure 6 shows the relationship between the cement content and the unconfined compressive strength of the laboratory mixing test. The strength of the ground improvement achieved using high-slag-content cement was almost equal to or higher than that achieved using the BB cement. Hexavalent chromium leaching was lower than 0.02 mg/L for both the high-slag-content cement and BB cement, which is lower than the limit specified in the environmental standard, MOE (1991).

Table 4. Laboratory and in situ cement contents and W/C conditions.

Construction site and soil type		Design Strength (N/mm^2)	Cement type	W/C (%)	Cement (kg/m^3) Lab.	In situ
Osaka	As1	1.8	High-slag, BB	80	150, 200, 350	150
Tokushima	As	1.5 2.1	High-slag, BB	80	100, 150, 250	115 160
Fukuoka	Fsc	2.0	High-slag, BB	70	150, 300, 450	200
	As				200, 350, 500	200

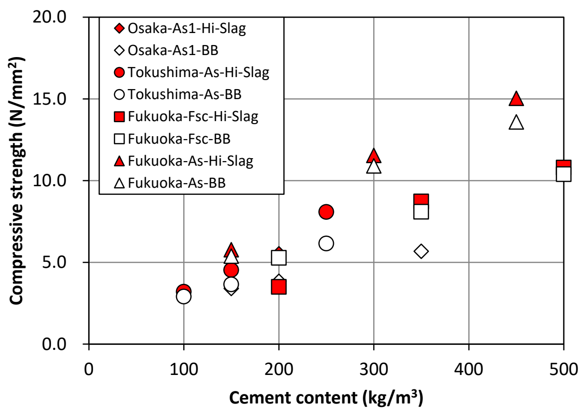

Figure 6. Relationship between the cement content and compressive strength in laboratory mix design test.

3.4 *Results for in situ ground improvement*

The field conditions determined based on the laboratory-mixed test results are listed in Table 4.Core samples were collected 9–21 days after construction using a Φ65-mm-diameter boring core sampler to investigate the strength of the ground improved in situ. From the collected samples, specimens were cut to a height of 100 mm, and unconfined compression tests were conducted 28 days after ground improvement construction.

Table 5 lists the unconfined compressive strength of the core samples collected from the ground improvement constructed in situ, the coefficient of variation in the unconfined compressive strength, and the ratio of field strength to laboratory strength (the field/laboratory strength ratio). The number of core samples varied with the site and cement type, and the average values and coefficients of variation were calculated for 9–27 samples.

The strength of the ground improvement achieved using high-slag-content cement satisfied the design strength requirements. In addition, the strength of the ground improved using slag cement was approximately equal to or lower than that using BB cement. Ground improvement using high-slag-content cement is more susceptible to the effects of drying than that using BB, which leads to cracking on the surface of the test specimens and decreased strength (Kono et al., 2018). For ground improvement at the Tokushima site, core samples were cured under dry conditions after extraction. Therefore, the strength of the ground improved using high-slag-content cement was lower than that of the soil improved using BB.

The coefficients of variation in the unconfined compressive strength of the core samples from the ground improved using high-slag-content cement were 16.5%–30.4% for the sandy soil and 17.3% for the cohesive soil. However, the coefficient of variation for the BB cement was 13.6%–39.6% for the sandy soil and 21.4% for the cohesive soil. The coefficient of variation for the ground improved using high-slag-content cement was similar to that of the BB cement and lower than the 20%–45% limit recommended in the Japan Building Center Guidelines (BCA, 2002).

The field strength–laboratory strength ratio is the ratio of the strength of the ground improvement constructed in the field to the laboratory strength under the same amount of cement. The field strength–laboratory strength ratios were 0.8–1.5 and 1.5 for the sandy and cohesive soils, respectively, when high-slag-content cement was used. The corresponding values for the BB cement were 0.8–1.8 (sandy soil) and 1.0 (cohesive soil). These values are higher than the lower-limit reference values of 0.59–0.6 specified in the Japan Building Center Guidelines (BCA, 2002).

Table 5. Compressive strength, coefficient of variation in unconfined compressive strength, and ratio of in-situ field strength to laboratory strength.

Construction site and soil type	Compressive strength (N/mm^2)		Coefficient of variation (%)		Ratio of in-situ strength to laboratory strength	
	High slag	BB	High slag	BB	High slag	BB
Osaka As1	2.8	2.9	30.4	35.8	0.6	0.8
Tokushima As	4.4	5,3	25.3	39.6	1.2	1.7
	5.4	7.1	16.5	18.3	1.0	1.8
Fukuoka Fsc	5.3	5.0	17.3	21.4	1.5	1.0
Fukuoka As	5.9	6.2	18.9	13.6	0.8	0.9

4 CONCLUSIONS

In this study, laboratory and in situ construction tests were conducted to develop and utilize high-slag-content cement with a BFS content of 60% or higher for ground improvement to reduce CO_2 emissions. The main conclusions of this study are as follows:

(1) The compressive strength of the ground improved using high-slag-content cement, both at the initial stage and after 28 days of curing, became equivalent or superior to that of BB cement when the OPC and CS content ratios were 30% and 5%, respectively.

(2) In the laboratory-mixed design tests conducted to construct the ground improvement specimens at the site, the strength of the ground improved using slag cement was equivalent to or slightly higher than that using BB cement. In addition, the amount of leached hexavalent chromium was smaller than the value recommended in environmental standards.

(3) The coefficients of variation in the unconfined compressive strength of the ground improved using high-slag-content cement were 16.5%–30.4% and 17.3% for the sandy and cohesive soils, which are similar to those of the BB cement.

(4) The field strength–laboratory strength ratios of ground improved using high-slag-content cement were 0.8–1.5 (sandy soil) and 1.5 (cohesive soil), respectively. These values were equivalent to those of the BB cement.

(5) The field strength–laboratory strength ratios and strength variations of the ground improved using high-slag-content cement exceeded the lower-limit values specified in BCA (2018).

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