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

https://doi.org/10.53243/ICEG2023-177

9ICEG

Properties of soil-cement wall using low CO_2 emission cement

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ABSTRACT

Cement manufacturing involves expensive raw materials, a high energy requirement, and excessive CO_2 emissions. To mitigate these disadvantages and realise an effective alternative for building soil-cement walls, a high-slag cement called *E*nergy and *C*O_2–Minimum cement (ECM) is proposed herein. Experimental tests were performed using two types of cement: ECM and BFS type B (BB), and their properties, such as strength, workability, and fluidity, were determined and compared. The results of this study confirm that the proposed ECM cement emits significantly low CO_2 emissions and can be used as a viable alternative to building soil-cement. Furthermore, in the future, the proposed cement can be used in in-situ construction equipment in the practical projects.

Keywords: CO_2 emission, high-slag cement, soil-cement wall, laboratory test, in-situ test

1 INTRODUCTION

The total emissions of CO_2 in Japan were 1.0 billion tons in 2020 (JCCCA, 2021). Because of these high emissions, it has become paramount to reduce the CO_2 output by improving the climate change policies. The production of cement in Japan was a maximum of 99.6 million tons in 1996, but recently, the production declined and in 2020 it was 55.7 million tons (Japan Cement Association, 2021a). And in 2020, 29.4 million tons was used for concrete (Japan Cement Association, 2020b) and 7.8 million tons was used for ground improvement (Japan Cement Association, 2020c). In addition, CO_2 emissions from cement production in Japan currently comprise approximately 4% of the total CO2 emissions of Japan. Theoretically, if CO_2 emissions from the production of cement for concrete manufacture and ground improvement are reduced, the CO_2 emissions in Japan can also be reduced.

Current research suggests that blast-furnace cement may be effective in reducing CO_2 emissions. Blast-furnace slag cement types A, B, and C used in Japan are defined in JIS5211 depend on the chemical compositions of blast-furnace slags. Blast-furnace slag cement that are produced by incorporating blast-furnace slags tend to exhibit low early-age strengths, high drying shrinkage, and high carbonation rate. Therefore, slag cement has not been so utilized in concrete structures. In the case of ground improvement, cement– based solidifying material are often utilized to prevent the elution of Cr (VI).

To reduce CO_2 emissions during cement production, new slag cement (ECM cement) containing >60% blast-furnace slag has been developed (Yonezawa et al., 2013). In this development, the reduction of CO_2 emissions were trying to achieve in cement production by replacing the OPC in concrete with ECM cement and replacing cement-based solidifying material with ECM cement in ground improvement.

In order to apply ECM cement for concrete, they considered application to high-strength reinforced concrete (Tuji et al., 2014), civil-engineered concrete (Hashimoto et al., 2014), cast in place piles concrete (Ogawa et al., 2014) have been examined. High-strength concrete can significantly reduce carbonation, and civil-engineered concrete have thick covers, cast in place piles concrete are unlikely to have carbonation and drying shrinkage occurrence because it is placed into the ground. Furthermore, the applications of ECM cement in foundation structures (Kono et al., 2015) and soil-cement columns (used in liquefaction countermeasures) were explored; subsequently, the CO_2 emission reduction effects, strength properties, and workability of the ECM cement were investigated (Kono et al., 2017).

In this paper describes the application of ECM cement to soil-cement walls utilized for earth retaining walls in excavation. Laboratory and in-situ tests were conducted to investigate the strength and flowability of soil cement using ECM cement. Based on the investigation results, it was confirmed that ECM cement can be utilised for soil cement and that it is highly effective in reducing CO2 emission.

2 PROFILE OF ECM CEMENT

ECM cement is a by-product formed during steel production. It comprises 60 to 70% blast furnace slag fine powder, which exhibits significantly low CO_2 emissions per unit—approximately 1/30 of that of ordinary Portland cement (OPC). Figure 1 shows the material composition of the ECM cement. By increasing the blast furnace slag fine powder content, it is possible to reduce the CO_2 emissions to 60 to 70% of that of ordinary Portland cement (OPC) and approximately 40% of that of BFS cement type B (BB), which is generally used in soil-cement columns and soil-cement walls.

When ECM cement with low Portland cement content is applied to soil cement walls with high water cement ratio, the following items should be checked: ① The required strength is obtained after 28 days of curing. ② A specified initial strength is ensured so that the equipment holding the H steel can be removed the day after the earth retaining wall is constructed.③ Fluidity and fluidity retention time required for insertion of H steel. The required strength after 28 days of curing was set at more than 0.5 N/mm^2 (The SMS 2002), the required strength after 1 day of curing was set at more than 0.1 N/mm^2, as an indicator of flowability, the flow value in the table flow test is set to be more than160 mm and secured for at least 2 hours.

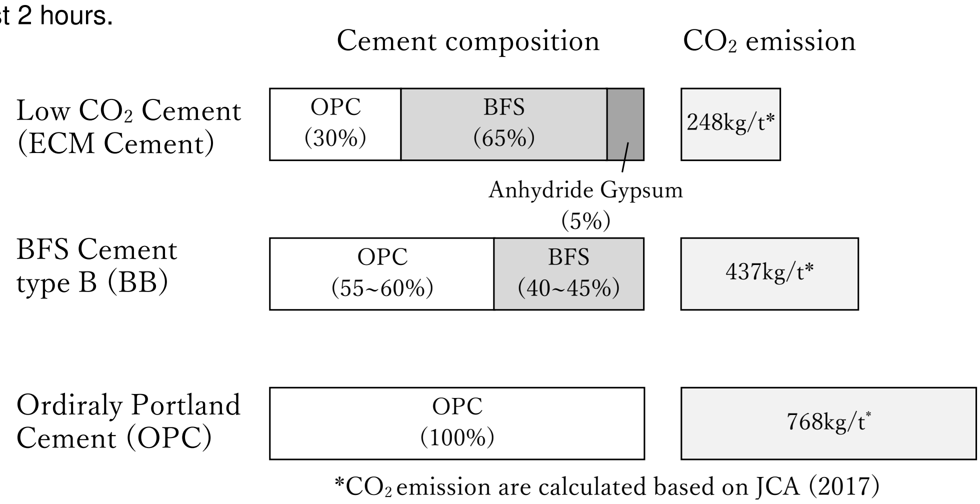

Figure 1. *Composition and CO_2 emissions of ECM, BB, and OPC cement, respectively (Japan Cement Association (2017)).*

3 LABORATORY EXPERIMENTAL TESTS

3.1 Test conditions

To confirm the applicability of ECM cement to soil cement, laboratory tests were conducted to compare strength and fluidity with commonly used BB cement. Since the strength and fluidity of soil- cement are greatly affected not only by the cement type but also by the ground types and conditions, ground samples were taken from the construction site where the in-situ construction test would be carried out. Table 1 shows the cement and bentonite chemical materials, and Table 2 shows the properties of the ground samples used in the tests. Two types of cement were used: ECM cement and BFS cement type B (BB). Ground samples were collected from the tuffaceous clay layer (Lc) and Tokyo layer (Tos) (see Fig.5), and a mixture of layer thicknesses (Lc layer and Tos layer) was used.

Table 3 shows the mixing conditions of the laboratory mixing tests to confirm the strength and workability of soil-cement manufactured in situ. The water cement ratio (W/C) of cement milk was set to 250%, and the amount of cement added was set to 200 kg/m^3. In the condition of using ECM cement, a test was also conducted under conditions where the cement addition amount was increased to 230kg/m^3, and the effect of cement addition on strength and fluidity was investigated. In this laboratory tests, the unconfined compressive strength and fluidity were investigated. For the strength, after curing 1 day to 28 days were examined. For fluidity, immediately after mixing to after 1 hour were examined.

Table 1. *Chemical composition of the cement*

Cement type	SiO_3	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3
ECM Cement	28.21	10.62	1.05	49.95	4.12	4.02
BB Cement	—	—	—	—	3.23	1.93
Bentonite	72.5	13.8	1.9	0.8	2.7	-

Table 2. *Soil properties*

Soil	Wet density (g/cm^3)	Water content (%)
Lc (5~11.2m)	1.51	81.0
Tos (11.2~26.3m)	1.81	29.4
Mixed soil (Lc:Tos=1:1.7)	1.77	48.5

Table 3 *Laboratory test conditions*

Cement type	W/C of cement slurry (%)	Amount of added cement (kg/m^3)	Amount of added bentonite (kg/m^3)
ECM Cement	250	230	13
ECM Cement	250	200	13
BB Cement	250	200	13

3.2 Test results

Figure 2 show the unconfined compressive strength observed in the laboratory mixing test. The unconfined compressive strength of the soil-cement using ECM cement was observed to be greater than the soil-cement using BB cement at each curing period. The strength of the soil cements using ECM cement and BB cement after curing 28 days excess the target value of 0.5 N/mm2. And the strength of using ECM cement after curing 1 day excess the target value of 0.1 N/mm2, but the strength of using BB cement below the target value. It was confirmed that using ECM cement for soil cement with a high water-cement ratio is effective.

Figure 3 show the 15-stroke flow value in the table flow tests in the laboratory mixing tests. It was noted that the table flow value of the soil-cement using ECM cement from immediately after mixing to one hour after mixing was slightly larger than that of the soil-cement using BB cement. And the tendency of the decreasement of flow value was observed to be the same for both cases. It was confirmed that the fluidity of soil cement using ECM cement was almost same as the using BB cement.

Furthermore, we confirmed that when the amount of cement added to the soil-cement using the ECM cement was 230 kg/m^3, both the strength and fluidity properties were improved compared to when the amount of cement added was 200 kg/m^3, thus confirming the effect of increasing the amount of added cement.

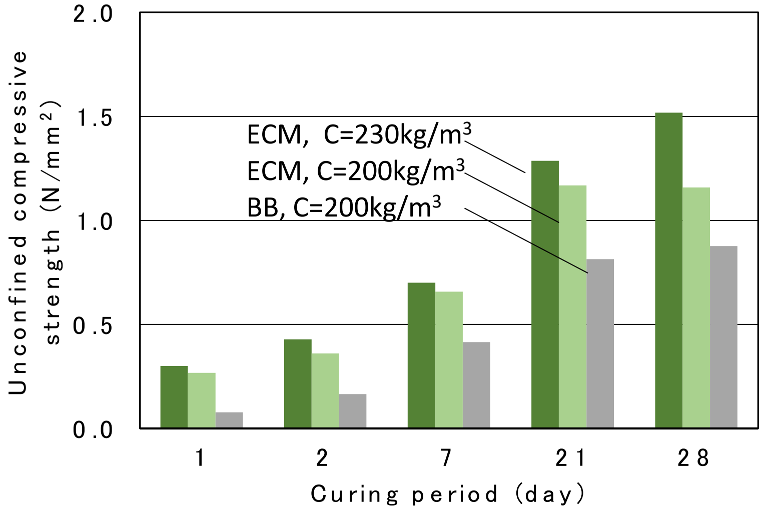

Figure 2. *Compressive strength of the soil-cement*

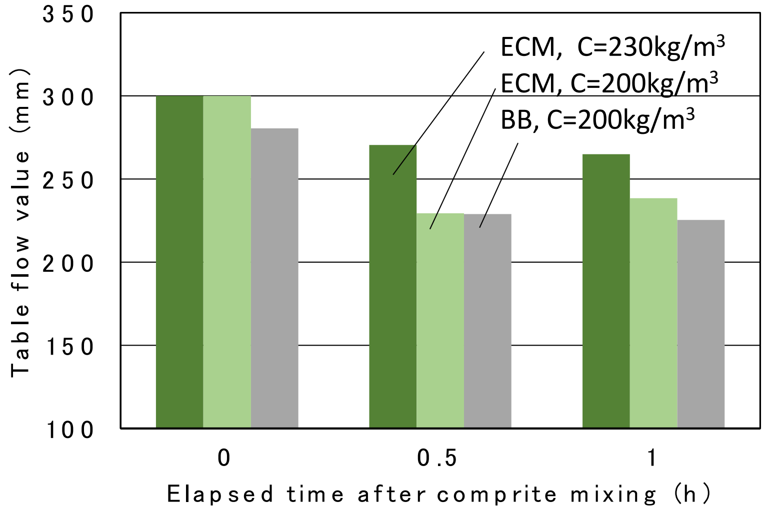

Figure 3. *Table flow of the improved soil*

4 IN-SITU TESTS

4.1 Construction and earth retaining wall

The new constructed building is an office building with a floor area of 64 m x 50 m, 3 underground floors, and 15 floors above ground (Kono et al., 2022). Figure 4 shows the floor plan of the underground construction of this building. The depth of the foundation bottom of this building are GL-17.2 m and GL -22.3 m. The retaining walls used for excavation were soil-cement walls; the tip depth of the core material, H-section steel, was GL-20 m and GL-24.5 m, depending on the excavation depth, and the tip of the soil-cement walls was GL-32 m. They penetrated approximately 2 m deep into the Ka layer, which may be regarded as a shielding layer. In the construction of the soil-cement walls, BFS cement type B (BB) was used, and ECM cement was applied to a part of the east face (see Figure 4).

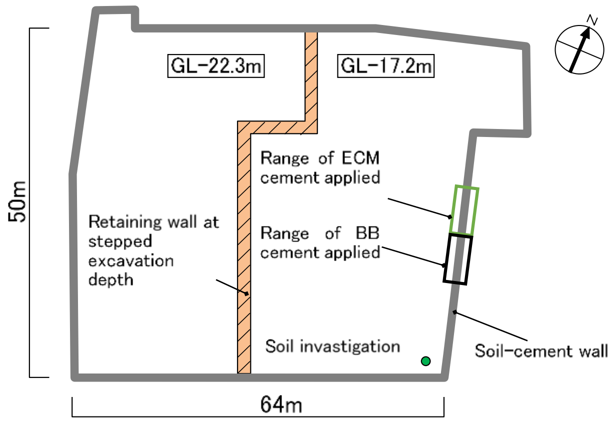

Figure 4. *Plan view of the building*

4.2 Ground conditions

Onsite boring survey results and laboratory test results are shown in Figure 5 (survey locations are shown in Figure 4). The ground is composed of the Kanto loam layer (Lm), tuffaceous clay layer (Lc), Tokyo layer (Tos, Toc), Tokyo gravel layer (Tog), and Kazusa group (Ka), deposited in order beneath the ground surface. The Tokyo layer is primarily comprised of sand layers, although the presence of some clay layers has also been reported. On the site, each soil layer is deposited almost horizontally. The groundwater level in the Tokyo layer (Tos) is approximately GL-12.5 m to -13.5 m.

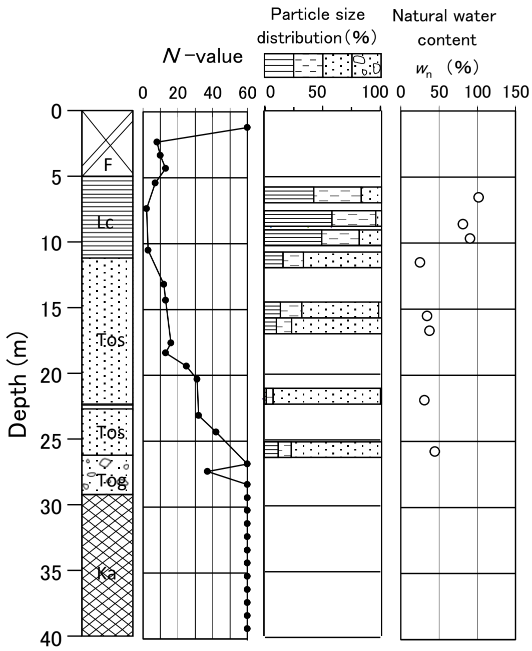

Figure 5. *Soil profile of the construction site*

4.3 Construction conditions

In the soil-cement walls constructed in situ, a three-axis soil-cement construction machine with a soil-cement diameter of φ0.9 m and intervals of 0.65 m between axes, a fully automatic plant creating cement milk, and a pressure pump for the cement milk were used. Figure.6 shows the soil-cement construction. Table 4 shows the mixing conditions in in-situ construction determined based on the laboratory mixing tests.

Table 5 shows the survey items and survey method for confirming the strength development and workability of the soil-cement manufactured in situ. To confirm the improvement in strength, strength tests were conducted using grab wet samples collected during soil-cement construction and extracted core samples from the excavation stage. In addition, we conducted table flow tests on grab wet samples collected during soil-cement construction. Furthermore, the grab wet samples subjected to uniaxial compression tests were sealed and cured on site after being packed in a mould.

Figure 6. *Overview of construction machine*

Table 4. *Construction conditions for in-situ construction*

Cement type	W/C of cement slurry (%)	Amount of added cement (kg/m^3)	Amount of added bentonite (kg/m^3)
ECM Cement	250	200	13
BB Cement	250	200	13

Table 5. *Summary of compressive strength in the field*

Investigation item	Investigation method	Detail
Compressive strength	Unconfined compressive strength	Grab wet sample during construction (GL-19.5 m) Extract core sample during excavation (GL-4.5 m、GL-6.0 m)
Fluidity	Number of H steel insertion	-

4.4 Results

Figure 7 shows the unconfined compressive strengths of grab wet samples collected during soil-cement manufacture. The wet sample strength of soil cement with ECM cement was higher than with BB cement up to 7 days of curing. But the wet sample strength of soil cement with ECM cement was lower than with BB cement after 21 days to 28 days of curing. In addition, if we compare the strength of grab wet samples and laboratory tests, that of grab wet samples is lower when ECM cement is used, and that of grab wet samples using BB cement is higher. In the case of soil-cement columns using ECM cement, it has been reported that their strength is lower than that of standard-cured samples owing to the curing temperature and drying conditions (Kono et al., 2018). The grab wet samples were subjected to sealed curing onsite, and the outside average temperature during curing period was 12.4℃; thus, the strength of the soil-cement using ECM cement was presumably lower.

Table 6 shows the unconfined compressive strength of extracted core samples. The strength of extracted core samples using ECM cement was higher than those using BB cement. Because these samples were cured in the ground prior to core sampling, it is inferred that the strength of soil-cement using ECM cement has been accurately evaluated. Although it is difficult to make a simple comparison due to the differences in the sampling method, sampling depth, and material age, it can be assumed that the strength development of the soil-cement using ECM cement is almost the same as that using BB cement.

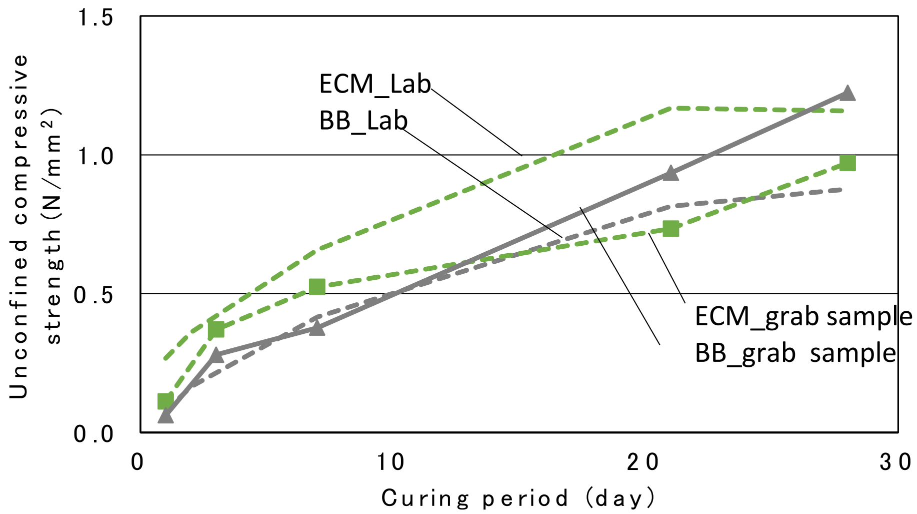

Figure 7. *Compressive strength of grab wet sample after curing*

Table 6. *Compressive strength of extract core sample in the field*

Cement type	Extract depth(m)	Curing period(days)	Compressive strength (N/mm^2)
ECM cement	GL-4.5	181	1.7
	GL-6.0	181	1.1
BB cement	GL-4.5	180	0.8
	GL-6.0	180	0.6

When the depth of soil-cement walls and length of H steel are high, the H-section steel may not be smoothly inserted, depending on the excavation accuracy of the soil-cement walls and the fluidity of the soil-cement. In this case, sometimes the H steel is once pulled-up and then re-inserted by dropping. Figure 8 shows the relationship between the elapsed time after soil-cement walls are completed and the number of insertion when the H steels are inserted, which are the stress material for the retaining walls. Since the construction site is almost the same and the construction machine is also the same, it is assumed that the construction accuracy of the retaining wall is almost the same, and the number of insertion of H steel indicated the fluidity of the soil-cement. When using BB cement, the number of H steel insertion range from 1 to 5 times, however when using ECM cement, the number are 1 time, leading to the conclusion that the soil-cement fluidity is high.

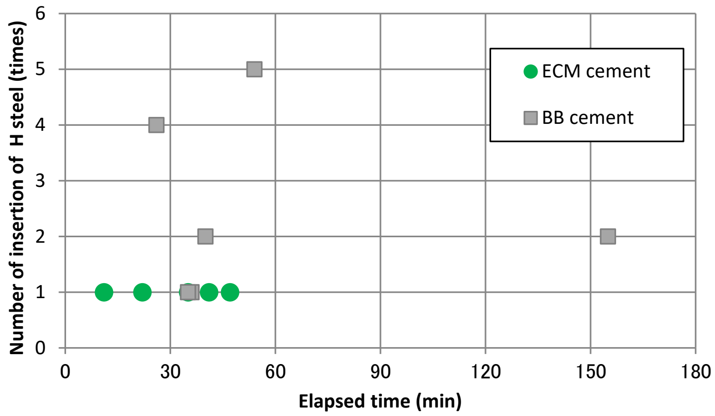

Figure 8. *Relationship between the elapsed and the number of insertion of H steel after completion of soil-cement construction*

4.5 Effect of CO_2 emission reduction

Table 7 shows the effect of reductions in CO_2 emissions in this project. The CO2 emissions of soil cement was calculated by multiplying the amount of added cement (see Table 4) by the CO2 emission of cement (see Fig.1). The CO_2 emission of the soil-cement using ECM cement was 50 kg/m^3. Using ECM cement in place of BB cement, CO_2 emissions could be reduced by approximately 45%.

Table 7. CO_2 emissions

Cement type	Amount of added cement (Table 4) (kg/m^3)	CO_2 emissions of cement (Fig.1) (kg/t)	CO_2 emissions of soil cement (kg/ m^3)
ECM cement	200	248	50
BB cement	200	437	87

5 CONCLUSIONS

In this study, low-CO2 emission ECM cement was used to build soil-cement walls. Laboratory mixing tests and in-situ construction tests confirmed that the soil-cement using ECM cement exhibited almost the same performance as that of the soil-cement using BB cement. It was found that CO2 emissions could be reduced by approximately 45% by using ECM cement for soil-cement wall instead of BB cement.

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