

Using a Polycarboxylic Acid-Based Surfactant to Improve the Quality of Cement-Treated Ground

by

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When cohesive surface soils are treated to create cement-based ground improvements, suppressing the aggregation of the clay particles with the cement-based solidifying material particles is an important consideration. Herein we evaluated a method that reduces the variation in the soil improvement body's strength by the generation of an electrical repulsive force between the particles due to the surfactant for aggregation suppression. The aggregation suppression mechanism was first verified by measuring the ζ -potential of the particles. The effect of reducing the variation in the soil improvement body strength was verified with an unconfined compression test using a specimen manufactured by indoor mixing. Finally, the effectiveness of the methodology was evaluated with on-site testing. Upon adding a surfactant, positively charged cement-based solidifying material particles have their potentials reduced, thereby becoming negatively charged. Therefore, electrical repulsion operates between these particles and the negatively charged clay particles, thereby preventing aggregation, increasing the fluidity of the soil-cement slurry, and reducing the variation in the strength of the soil improvement body. Finally, the effectiveness of the methodology was confirmed by on-site testing.

Key words:

Cement-treated ground, Surfactant, ζ -potential, Unconfined compressive strength, On-site testing

1 Introduction

For cement-treated ground, characteristics, such as large variations in the physical constants of the soil improvement body, have been problematic in the design and construction of these structures. One possible cause of these variations is the presence of a large fines content, resulting in a high viscosity of the soil-cement slurry during the solidification process. This is due to the hydration reaction of the cement-based solidifying material (hereafter, "solidifying material"), making it impossible to sufficiently agitate and mix the soil-cement slurry. A previous study¹⁾ reported the properties of a soil-cement slurry and indicated that the viscosity of the soil-cement slurry changed over time and the condition of false solidification was influenced by the unique properties of the soil to be treated. In general, clay is negatively charged, such that it creates an environment that easily allows adhesion to the calcium ions of the cement component included in the solidifying material. Herein we evaluated a method of solidification that mixed the solidifying material into cohesive soil with few polyvalent ions, as shown in Figure 1(a), and a method that mixed the solidifying material into cohesive soil with many polyvalent ions, as shown in Figure 1(b). When the mixture contained few polyvalent ions, there is little opportunity for positive ion exchange. This results in a low level of adhesion with the calcium ions in the solidifying material, making it difficult for aggregated bodies

to form. By contrast, mixtures containing many polyvalent ions displayed greater adhesion between the cohesive soil and the solidifying material, resulting in the formation of aggregated bodies and creating a network of aggregated bodies that holds water in the soil to increase the viscosity of the soil-cement slurry.

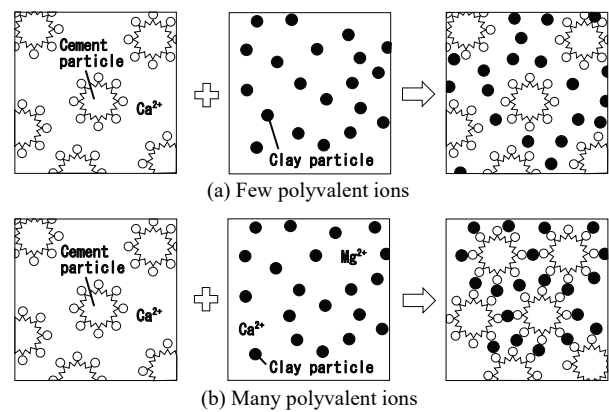


Fig. 1 Outline of aggregation.

Herein we examine the effect of reducing variations in the physical constants of the soil improvement body by adding a surfactant during the preparation of the cement slurry. This was part of a method in which the cement slurry was homogeneously dispersed in the medium, not just by the mechanical force of a mixer, but also by the repulsive force due to the surfactant. In a previous study²⁾, we investigated

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the fluidity of soil-cement slurry and the unconfined compressive strength of the soil improvement body upon adding surfactant by indoor mixing. It was confirmed that addition of surfactant leads to improved quality of the soil improvement body. A surfactant having a high dispersing effect was selected and the optimum addition amount was determined. Furthermore, effect of quality improvement of the soil improvement body upon surfactant addition was examined at four sites. However, it was not verified whether an electrical repulsive force was generated between the soil particle and the cement-treated solidifying material.

Accordingly, in this paper, the generation of an electrical repulsive force due to the surfactant was verified in terms of the ζ -potential values of the solidifying material particles and the soil particles, as measured by microscopic electrophoresis. In addition, the effect of the surfactant on the degree of soil-cement mixing and the strength characteristics of soil improvement body were confirmed by performing indoor mixing tests on the soil samples used for the ζ -potential measurement. The effectiveness of the surfactant in quality improvement of the cement-treated ground was evaluated by adding field test results at two new sites to the previous test results at four sites².

There have been several examples of research^{3~6} into the fabrication of soil-cement using a cement slurry with a surfactant additive. However, this research has not produced a consistent evaluation that verifies the mechanism based on measuring particle potentials by examining the effect of reducing variations in the strength of the soil-cement.

2 The Electrical Characteristics of the Solidifying Material Particles and the Soil Particles

2.1 Overview of the ζ -Potential and its Measurement Method

Figure 2 is a schematic diagram of the ζ -potential. For example, if negatively-charged particles are present, positively charged ions will surround those particles to form a Stern layer^{7,8}. Around this Stern layer, a diffuse layer forms that is a mixture of ions with positive and negative charges. Due to shear forces that are generated when the particles move, a portion of the ions move with the particle and a portion of the ions move away from the particle within the diffuse layer, and a boundary surface (slipping plane) is formed between them. The potential in the slipping plane is called the ζ -potential^{7~9}.

At present, there is no established methodology for directly measuring the surface potential of a particle. Therefore, the ζ -potential is generally taken to be the surface potential.

The ζ -potential was examined by microscopic electrophoresis¹⁰. In electrophoresis, an electric field is applied to a solvent containing particles, so that particles with

a positive charge move toward the negative electrode, particles with a negative charge move toward the positive electrode, and the ζ -potential is found by using image processing to track and measure the ease of movement per unit time. This measurement method included the following steps:

- (1) Place the specimen in a beaker, add ion-exchanged water or pH-adjusted water, and agitate for one minute with a glass rod to prepare the measurement solution.
- (2) Put the measurement solution into the measurement equipment.
- (3) Perform measurements continuously until obtaining a given amount of image data.
- (4) Manually track the particles from the obtained image data to find the ζ -potential.

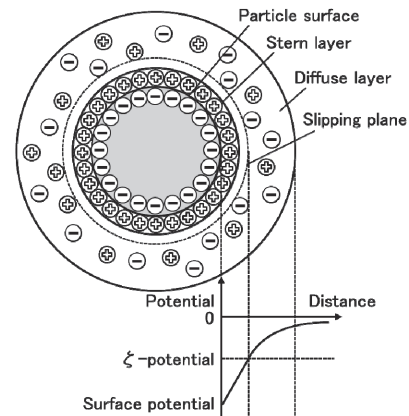


Fig.2 Outline of ζ -potential.

2.2 Measurement Conditions

Table 1 summarizes the measurement conditions. The specimens can be characterized as kaolin clay, loam, and solidifying material. Cases 1-1 and 1-2 provide the measurement conditions for kaolin clay and loam. Case 1-3 provides the measurement conditions for the solidifying material particles alone, and Case 1-4 provides the conditions when a polycarboxylic acid-based surfactant (hereafter, "surfactant") is added to the medium of Case 1-3, with the amount of surfactant equal to 10% of the mass of the solidifying material. Figure 3 and Table 2 provide the present grain size distribution and physical properties of the soil, and Table 3 presents the characteristics of the surfactant.

Table 1 Test case of ζ -potential measurement.

Case	Sample	Types of water	Water amount (cc)
1-1	Kaolin clay (0.03g)	Ion exchange water	300
		pH adjusted water	
1-2	Loam (0.03g)	Ion exchange water	
		pH adjusted water	
1-3	Cement-based solidifying material (1.5g)	pH adjusted water	
1-4	Cement-based solidifying material (1.5g) with Polycarboxylic acid-based surfactant (0.15g)		

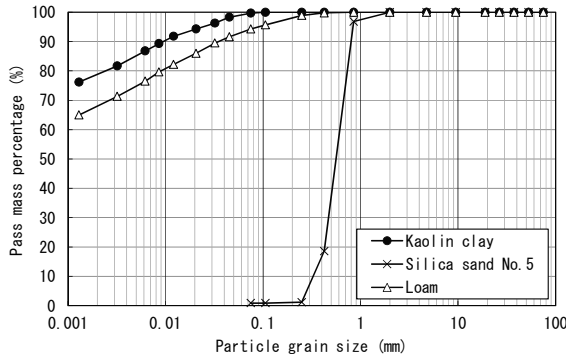


Fig. 3 Particle grain size distribution of test soil.

Table 2 Test soil characteristics.

	ρ_s (g/cm ³)	ρ_{dmin} (g/cm ³)	ρ_{dmax} (g/cm ³)	Ip
Kaolin clay	2.748	-	-	30.2
Silica sand No.5	2.667	1.578	1.278	
Loam	2.801	-	-	30.4

Table 3 Surfactant characteristics.

Appearance	Liquid of light brown color
Specific gravity	About 1.29
pH value	About 8
Molecular weight	About 12000
Solubility	Soluble in water

In general, cohesive soil particles are negatively charged, and cement particles are positively charged, and as the pH environment changes, the potentials of the fine particles also change^{10,11}. It is possible that during cement-based ground improvement, the treated ground becomes an alkali environment, due to the effect of the solidifying material.

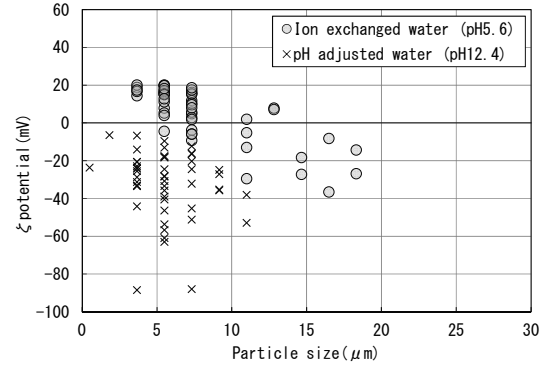
Prior to adding the solidifying material to ion-exchanged water (pH 5.6), the pH of the solidifying material solution was tested (pH 12.4). Based on the collected pH data, the measurement of soil particles in this test was conducted using ion-exchanged water and pH-adjusted water to model the conditions within the treated ground. The pH was adjusted to 12.4 by dissolving sodium hydroxide (NaOH) in ion-exchanged water.

2.3 Measurement Results

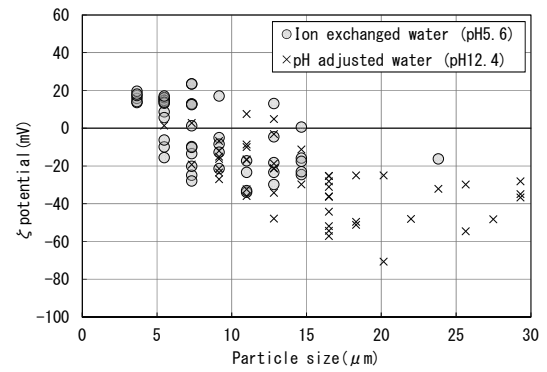
Figure 4(a) shows the ζ -potential of the kaolin clay particles in Case 1-1. In ion-exchanged water, particles may be positively or negatively charged; however, in pH-adjusted water, the potential is lower and all the particles are negatively charged. This trend is similar to the results for the loam in Case 1-2, as shown in Figure 4(b).

Figure 4(c) presents the ζ -potentials of the solidifying material particles alone and the solidifying material particles in a medium to which surfactant has been added, which correspond to Cases 1-3 and 1-4, respectively. Solidifying material particles alone are positively charged, and the addition of the surfactant lowers the potential, making the particles negatively charged.

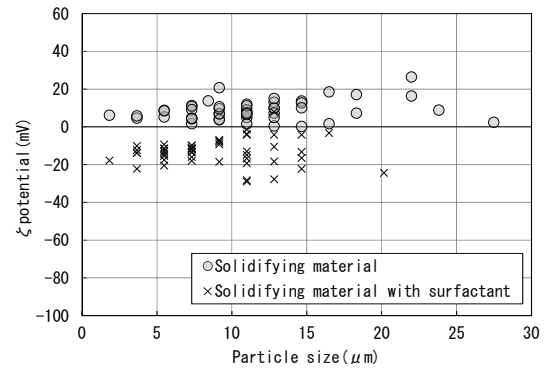
These results indicate that using a surfactant makes both the soil particles and the solidifying material particles negatively charged, thereby causing electrical repulsion between the two kinds of particles and preventing the formation of aggregated bodies.



(a) Kaolin clay



(b) Loam



(c) Cement-based solidifying material and cement-based solidifying material with surfactant

Fig.4 Test results of ζ -potential.

3 Verification of the Effect of Reducing the Variation in Soil Improvement Body Strength, Based on an Indoor Mixing Test

3.1 Test Conditions

The experimental results described in Section 2 indicated that electrical repulsion, which is the mechanism by which the surfactant reduces variation in strength of the soil improvement body, operates between clay particles and solidifying material particles. To verify the fluidity improvement of the soil-cement slurry, a hand vane shear test

was performed to evaluate the effect of suppressing the aggregation in the soil-cement slurry. An unconfined compression test on a soil improvement body was also performed to verify the effect of reducing the variation in strength.

Table 4 presents a list of the test cases. Specimen soils were created by mixing the soils, as shown in Table 2, with the percentages shown in Table 4(a). Cement slurry was added in the percentages presented in Table 4(b) relative to the mass of the test soil. A predetermined amount of the surfactant was dissolved in the solidifying material solution relative to the weight of the solidifying material. We agitated and mixed these test soils and the cement slurry in a mixer to create the soil-cement slurry. The agitating blades of the mixer are shown in Figure 5, and the agitation conditions are shown in Table 5.

Table 4 Test cases.
(a) Soil samples

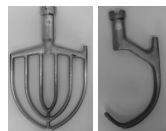
Soil sample	Soil content		Water content
Cohesive soil	Kaolin clay	Silica sand No.5	70%
	70%	30%	
Sandy soil	Kaolin clay	Silica sand No.5	30%
	40%	60%	
Loam	Loam 100%		100%

(b) Test conditions of indoor mixing test

Soil sample	Cement-based solidifying material		Polycarboxylic acid-based surfactant	
	Addition percentage (%)	W/C (%)	Addition percentage (%)	
			Hand vane shear test	Unconfined compression test
Cohesive soil	10	60	0.0, 0.2, 0.4, 1.0	0.0, 0.2, 0.4, 1.0
Sandy soil	10		-	
Loam	20		-	

Table 5 Agitating conditions.

Soil sample	Hand vane shear test		Unconfined compression test	
	Agitating time	Agitation blade	Agitating time	Agitation blade
Cohesive soil	2min.	Type A	1min.	Type B
Sandy soil	-	-		
Loam	-	-		



Type A Type B
Fig.5 Agitation blade.

3.2 Test Methods

(1) Hand Vane Shear Test

The test equipment is shown in Figure 6. The test body was created by inserting the soil-cement slurry into a container of width 350 mm, depth 180 mm, and height 210 mm. In the test, a hand vane with a cross-shaped blade of height $H = 40$ mm and width $D = 20$ mm was rotated by hand to maintain a rotation speed of 1 deg./min, and the maximum torque was measured. Measurements were made a total of three times: immediately after mixing, 30 minutes after mixing, and 60 minutes after mixing the soil-cement slurry. Measurements were taken at five locations each time. The

value of the shear strength is expressed by formula (1):

$$\tau = \frac{M_{max}}{\pi(D^2H/2 + D^3/6)} \quad (1)$$

Where τ is the value of the shear strength (kN/m^2), M_{max} is the maximum torque ($\text{kN}\cdot\text{m}$), D is the width (m) of the blade of the hand vane, and H is the height (m) of the blade of the hand vane. The shear strength values measured each time are averages of the measurement results for the five measurement locations and were used for the subsequent investigation.

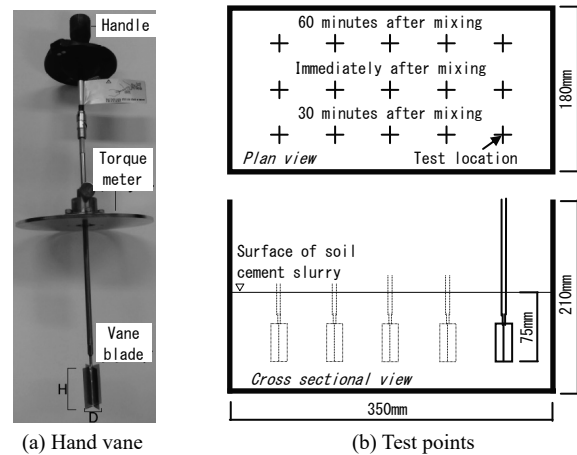


Fig.6 Outline of hand vane shear test.

(2) Unconfined Compression Test

The unconfined compression test was performed using the following steps:

- (1) The soil-cement slurry is divided into three portions and each of them was cast into a mold of diameter $\varnothing = 50$ mm and height $h = 100$ mm. After casting the soil-cement slurry each time, the mold was tapped ten times by hitting it against the floor.
- (2) Twenty manufactured test bodies were cured for seven days in a constant-temperature constant-humidity chamber with a temperature of 20° and a humidity of 60%.
- (3) An unconfined compression test was performed on the twenty test bodies to find the unconfined compressive strength and its coefficient of variation.

3.3 Test Results

(1) Hand Vane Shear Test

Figure 7 shows the change in the value of the shear strength over time for each addition percentage of surfactant. When the addition percentage was 0% (hereafter, "no surfactant addition"), the value of the shear strength, from immediately after mixing to 60 min after mixing, was larger than in the cases where surfactant was added, and the rise in the shear strength value over time was also larger. In cases where surfactant was added, larger addition percentages resulted in smaller shear strength values, and the increase in

shear strength over time was also gradual. These results indicate there was an improvement in the fluidity of the soil-cement slurry, resulting from the aggregation between clay particles and the solidifying material particles through the addition of the surfactant. This suggests that, in actual construction, this method will also contribute to reducing the agitation resistance load on the construction equipment.

(2) Unconfined Compression Test

Figure 8 shows the relationship between unconfined compressive strength and the addition percentage of surfactant. Compared to cohesive soil and loam, sandy soil in general has a smaller variation and a larger unconfined compressive strength. Moreover, for all types of soil, a comparison of mixtures with no surfactant addition and surfactant addition indicates there is little difference in the magnitude of the unconfined compressive strength. A surfactant has a delayed effect with regard to expressing strength, though it is also possible that no decrease in strength was observed because the amount of surfactant added was small, or because the solidifying material particles were well dispersed in the soil-cement slurry to create a relatively homogeneous test body.

Figure 9 shows the relationship between the coefficient of variation of the unconfined compressive strength and the addition percentage of surfactant. For sandy soil, it is difficult for aggregated bodies to form and agitating the mixture is easy because the coefficient of variation is inherently small. Accordingly, it was not possible to verify a change in the coefficient of variation due to the added surfactant. However, for cohesive soil and loam, it was possible to verify the coefficient of variation was approximately 45% with no surfactant addition case, but greatly decreased with the addition of at least 0.4% of surfactant.

4 On-Site Verification Test

To evaluate the effect of improving the quality of cement-treated ground by using a surfactant, a deep mixing method, which is a representative method, was used to perform an on-site verification test. Herein, the effectiveness of the surfactant in quality improvement of the cement-treated ground is evaluated by adding field test results at two new sites to the test results obtained at the four previously mentioned sites²⁾.

4.1 Test Sites and Test Conditions

Figure 10 shows soil profiles of the test sites and Table 6 shows the construction conditions of the soil improvement bodies. The test was done at six sites. Sites A and C were silty and sandy ground, B, D, E, and F were loam and clay ground. The diameter of the soil improvement body was 0.6 m and the length of the soil improvement body was 3 m, the same for all sites. We performed core removal of the black hatched regions in the elevation profiles of the soil improvement

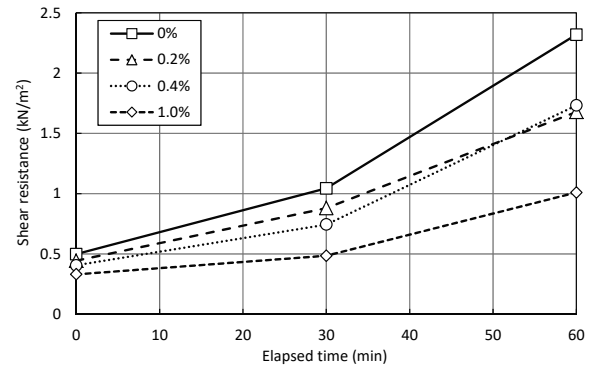
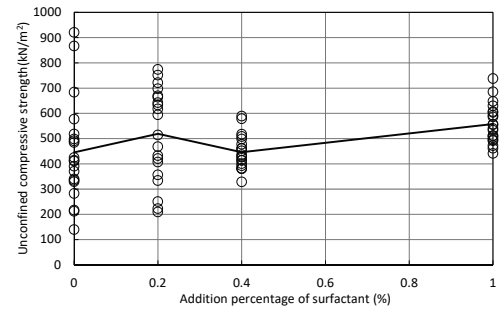
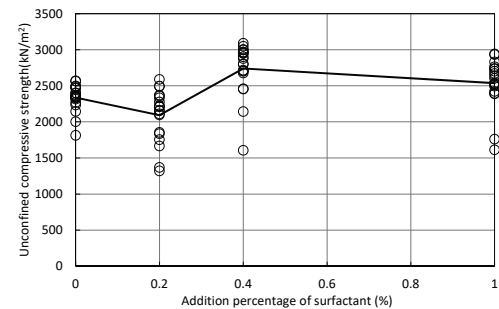


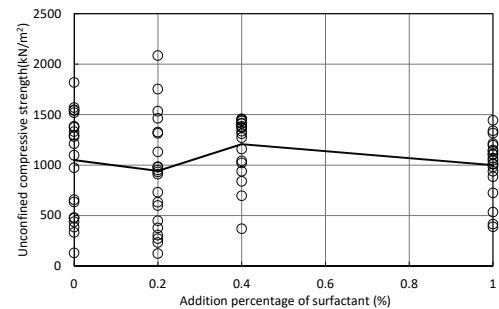
Fig. 7 Hand vane shear test results.



(a) Cohesive soil



(b) Sandy soil



(c) Loam

Fig. 8 Relationships between unconfined compressive strength and addition percentage of surfactant.

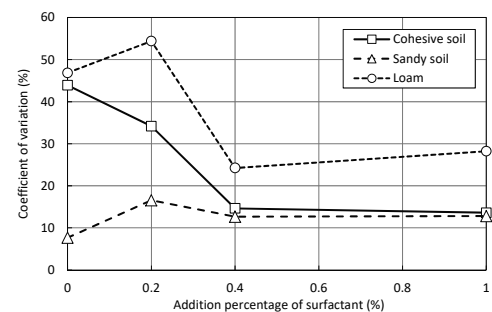


Fig. 9 Relationship between coefficient of variation and unconfined compressive strength.

bodies depicted in Fig.10. For all sites, the only construction variable was the addition of a surfactant. Other construction conditions were the same for each site, and the quality of the soil improvement body was evaluated after the construction.

Based on prior mixing test results using soil samples obtained from all the sites, the addition percentage of the surfactant was set at 1% (percentage of the mass of the solidifying material), which showed the maximum compressive strength. Table 7 shows an example of the relationship between the unconfined compressive strength and the addition percentage of surfactant after a curing time of seven days in the prior mixing test. If the addition percentage of surfactant exceeded 1%, the compressive strength decreased. As shown in Figure 11, in addition to the dispersion effect due to fluidization, the addition of the surfactant inhibited separation of material due. This was due

to the lowering of the viscous resistance of the slurry accompanying the apparent increase in the unit water content, which inhibited the hydration reaction.

The soil improvement body was created using an agitator provided with the corotation prevention blade shown in Figure 12, and with the construction cycle shown in Figure 13. The torque on the construction machine was also measured during the creation.

Quality verification was performed after a curing time of four weeks. The soundness of the soil improvement body was verified with an integrity test (IT test¹²) (Figure 14). In addition, the shape of the dug-out soil improvement body was inspected, and the dug-out soil improvement body was cut horizontally to a depth of 33 cm, with cores extracted at five locations in each cutting plane. These cores were then used to perform an unconfined compression test. Figure 15 shows the dug-out condition of a pile, and Figure 16 shows the condition after the cutting.

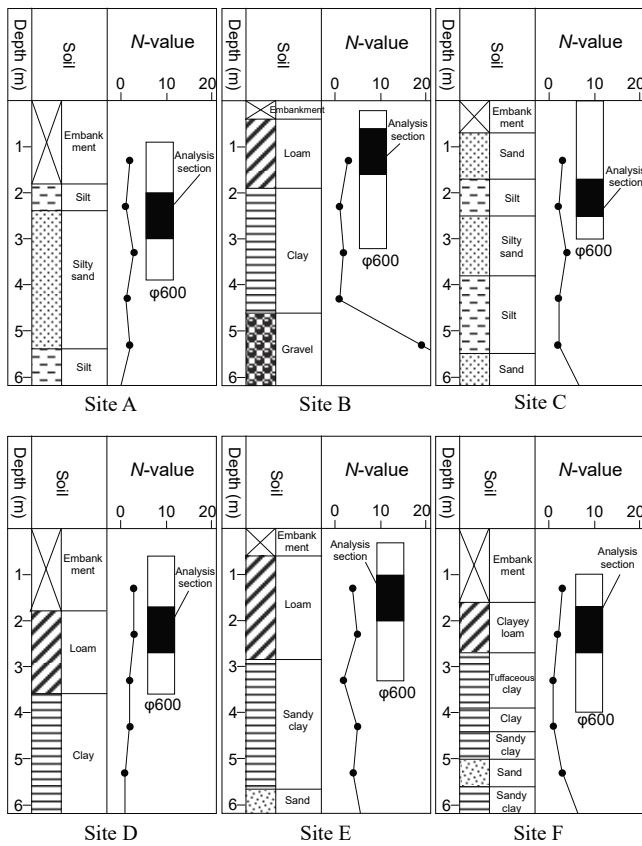


Fig.10 Test site.

Table 6 Pile composition conditions.

Test site	Type of Pile	Soil profile	Pile		Solidifying material		Surfactant addition percentage (%)	Core sampling number
			Diameter (mm)	Length (m)	Addition amount (kg/m ³)	W/C (%)		
A	A-1	Silt	600	3.00	280	60	0.00	5/0.33m
	A-2	Sand	600	3.00	280	60	1.00	
B	B-1	Loam	600	3.00	300	65	0.00	
	B-2	Clay	600	3.00	300	65	1.00	
C	C-1	Silt	600	3.00	250	65	0.00	
	C-2	Sand	600	3.00	250	65	1.00	
D	D-1	Loam	600	3.00	300	65	0.00	
	D-2	Loam	600	3.00	300	65	1.00	
E	E-1	Loam	600	3.00	300	65	0.00	
	E-2	Loam	600	3.00	300	65	1.00	
F	F-1	Loam	600	3.00	300	65	0.00	
	F-2	Clay	600	3.00	300	65	1.00	

Table 7 Example of average of unconfined compressive strength by using surfactant.

Addition percentage of surfactant (%)		0	1	2	3	4	5
Unconfined compressive strength (kN/m ²)	Silt	4000	6300	3900	2500	2200	2200
	Clay	500	700	700	700	400	500

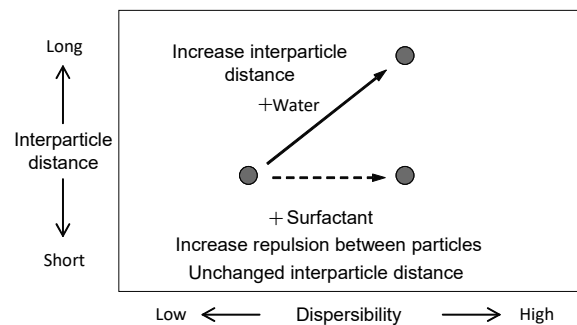


Fig. 11 Effect by addition of surfactant.

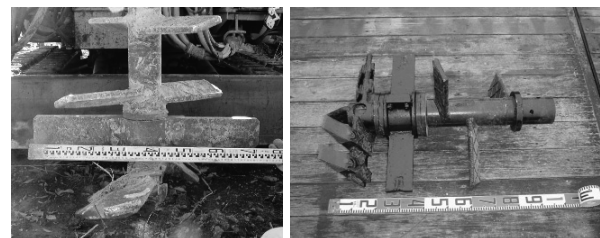


Fig. 12 Ground improvement agitator provided with corotation prevention blade.

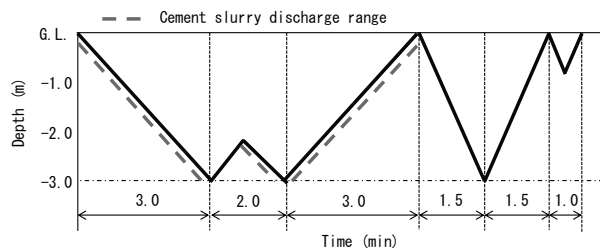


Fig. 13 Example of construction cycle.



Fig. 14 Pile Integrity Test situation.



Fig. 16 Pile cutting situation.



Fig. 15 Test trenching situation.

4.2 Test Results

Figure 17 shows an example of the torque changes over time, as measured in the construction equipment during fabrication of the soil improvement body. The torque decreased due to the addition of surfactant, indicating the fluidity of the soil-cement slurry increased due to addition of surfactant. This may also suggest that the addition of surfactant may contribute to improving construction efficiency.

Figures 18 and 19 show examples of IT test results. In the IT test, the top of the soil improvement body was tapped with a hammer, and the reflected wave was measured with an accelerometer placed on the top of the soil improvement body. For A-1 and B-1, which had no surfactant addition, disruption of the reflected waveform compared to A-2 and B-2 in which surfactant was added was verified, indicating the velocity of the reflected wave inside the soil improvement body was not constant. The portion where the velocity changed indicates variations in strength or a defect in the cross-section.

Figures 20 and 21 show the mean value and coefficient of variation of the unconfined compressive strength of the core test body. The mean unconfined compressive strength was approximately the same regardless of whether surfactant was added. On the other hand, the coefficient of variation of the unconfined compressive strength clearly decreased due to the addition of surfactant. The coefficient of variation of unconfined compressive strength decreased from an average of 31% to 23% for silty and sandy ground and from an average of 54% to 38% for loam and clay grounds, such that the suppression of variation was even more remarkable.

Based on these results, the quality of the soil improvement body improved due to the addition of a surfactant, and the soil and solidifying material could be homogeneously agitated and mixed.

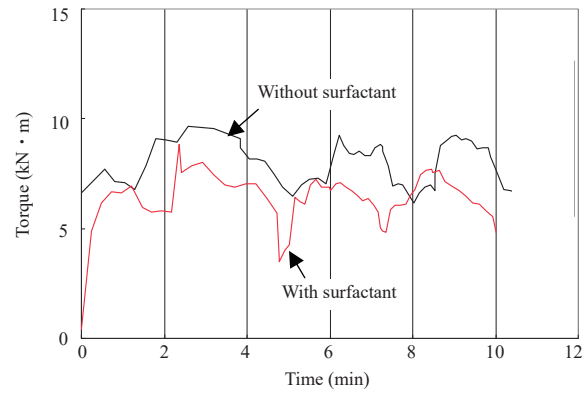
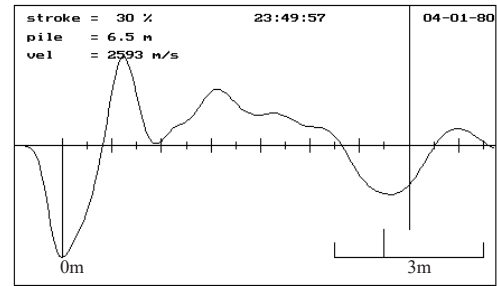
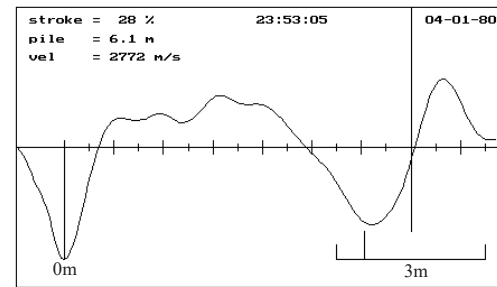


Fig. 17 Difference of the rotary torque in the silt ground.

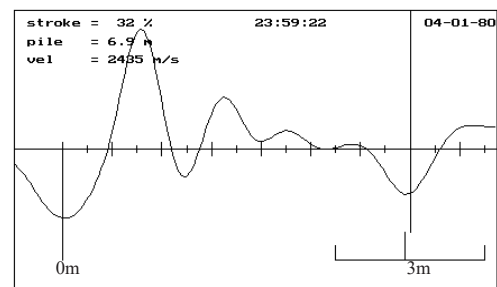


TypeA-1

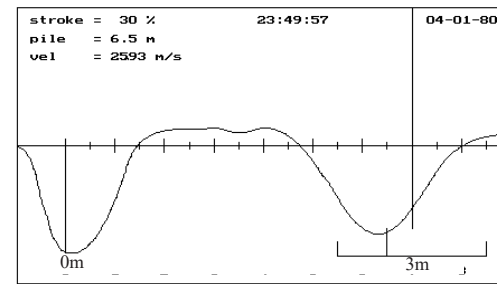


TypeA-2

Fig. 18 Pile Integrity test results of Site A.



TypeB-1



TypeB-2

Fig. 19 Pile Integrity test results of Site B.

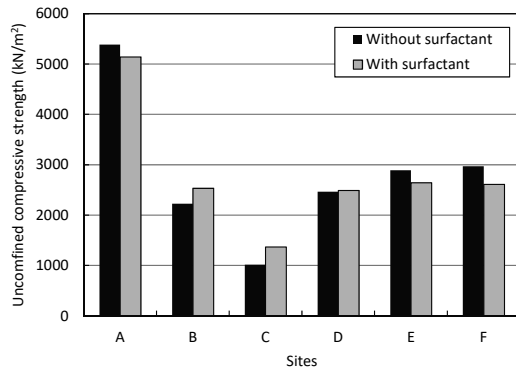


Fig. 20 Average of unconfined compressive strength of each site.

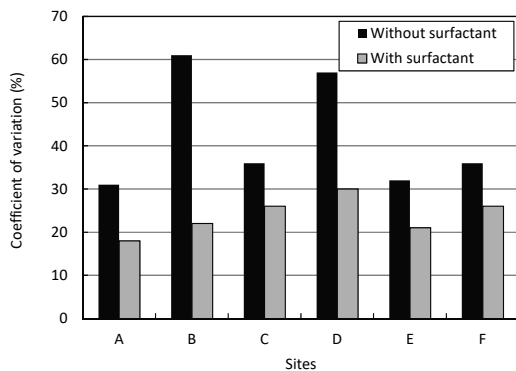


Fig. 21 Coefficient of variation of each site.

5 Conclusions

With respect to cement-based ground improvement using cohesive soil, the results of this study verified the effectiveness of a method that used a surfactant (a polycarboxylic acid-based surfactant) to suppress the aggregation of clay particles and cement-based solidifying material particles, thereby reducing variation in the strength of the soil improvement body. The results of this study further suggested the following conclusions:

- (1) Positively charged cement-based solidifying material particles have their potentials reduced by the addition of a surfactant, thereby becoming negatively charged, so that electrical repulsion operates between them and the negatively charged clay particles, making it possible to prevent aggregation.
- (2) Suppressing aggregation through the addition of a surfactant resulted in an increase in the fluidity of the soil-cement slurry, while the variation in the strength of the soil improvement body decreased.
- (3) The result of on-site testing at six sites was that, due to addition of surfactant, the torque on the construction equipment during agitating and mixing of the soil and cement slurry decreased, and variation in the strength of the soil improvement body was suppressed.

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