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POTENTIAL FOR SILICA-BASED SOLIDIFICATION MATERIALS AS SOIL IMPROVING AGENTS

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ABSTRACT: In a series of studies, the authors have developed a powdery silica-based solidification material composed of heat-treated inorganic solid wastes with a high content of silica products (such as waste glass and waste fly ash) mixed with alkali aids. This material is most suitable for use with iron or steel slag, such as that which comes from a blast furnace or a steel-making process. The powdery silica-based solidification material mixed with iron and steel slag can be expected to exhibit higher mechanical strength and more predominant characteristics than a powdery cement-based solidification material. In this study, the solidification mechanism for the mixture of the silica-based solidification material, blast furnace slag and water is clarified from the viewpoints of chemistry and mineralogy by conducting X-ray diffraction analysis, X-ray fluorescence spectrometry and inductively coupled plasma spectroscopy.

Keywords: Blast-furnace slag, Silica-based solidification material, Solidification mechanism, Waste glass

1. INTRODUCTION

In Japan, while natural resources are being steadily depleted, emissions of waste are increasing year after year. In a series of studies, the authors have developed a new solidification material using waste glass discharged from glass industries for the purpose of reducing and effectively using waste glass and blast furnace slag to prevent the depletion of natural resources [1]. However, although the mechanism for curing the mixture of silica-based solidification material, blast furnace slag, and water has been clarified, the solidification mechanism has not. In this study, the solidification mechanism is clarified from the viewpoints of chemistry and mineralogy by conducting X-ray diffraction analysis (XRD analysis), X-ray fluorescence spectrometry (XRF analysis) and inductively coupled plasma spectroscopy (ICP analysis). The applicability of ground-improvement methods, such as mechanical stirring and high-pressure injection mixing, to the material is also clarified through laboratory blended tests with sandy and clayey materials.

2. A POWDERY SILICA-BASED SOLIDIFICATION MATERIAL COMPOSED OF INORGANIC SOLID WASTES AND BLAST FURNACE SLAG

2.1 Basic composition of a powdery silica-based solidification material

The new powdery silica-based solidification material is composed of heat-treated inorganic solid wastes with high contents of silica products (such as waste glass and waste fly ash) mixed with alkali aids for drying and grinding. The main chemical components of this material are clarified by XRF analysis, and the results are shown in Table 1. As shown in the table, the main chemical components include silicon dioxide, sodium oxide and carbon dioxide. Further, the main mineral components of the powdery silica-based solidification material are clarified by XRD analysis; as shown in Fig. 1, these components are sodium meta-silicate and calcium carbonate. The clear peak in the figure indicates that the powdery material has a crystalline structure. Therefore, the material has a dense structure, which is excellent for preventing acid infiltration [2].

2.2 Basic composition of blast-furnace slag powder

Blast-furnace slag powder is blast-furnace slag with a specific surface area that has been adjusted to be more than 4,000 or 6,000 cm^2/g. It is used in concrete admixtures for its high-strength, high-flow and low-heat-build-up properties. Powder with a specific surface area of 3,000 to 4,000 cm^2/g is used as a material in general blast-furnace cement. Japanese Industrial Standards (JIS) has manufactured concrete blast-furnace slag powders with specific surface areas of 3,000, 4,000, 6,000 and 8,000 cm^2/g [3]. We clarify the main chemical components of this powder by XRF analysis and find that they include calcium oxide, silicon dioxide, aluminum oxide and magnesium oxide (see Table 2). Furthermore, Fig. 1 shows that blast-furnace slag powder lacks the clear peaks of the powdery

Table 1 The results of XRF analysis of the silica-based solidification material

Chemical composition	Contents (%)
SiO_2	41.7
Na_2O	37.8
CO_2	9.1
CaO	5.8
MgO	2.5
Al_2O_3	1.3

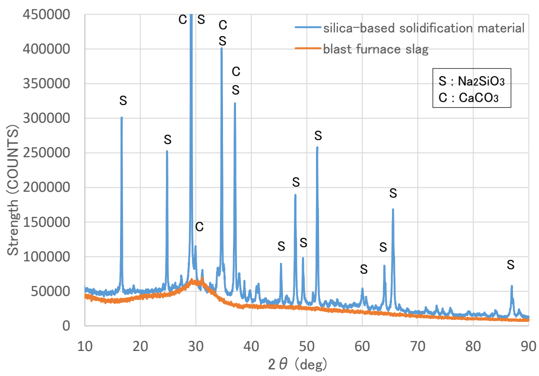

Fig. 1 The results of XRD analysis of the silica-based solidification material

Table 2 The results of XRF analysis of the cement-based solidification material

Chemical composition	Contents (%)
CaO	42.0
SiO_2	29.6
Al_2O_3	13.8
MgO	5.2
CO_2	5.2
SO_3	2.0

silica-based solidification material. Because a low-strength broad peak is found, the powder is suggested to be unstable and amorphous, with good reactivity.

3. SOLIDIFICATION MECHANISM OF THE MIXTURE OF THE SILICA-BASED SOLIDIFICATION MATERIAL AND BLAST-FURNACE SLAG

From the results of the ICP analysis of the silica-based solidification material, as presented in Table 3, the elution of large quantities of Si, Na and Ca is

Table 3 The results of ICP analysis of the silica-based solidification material

	extract from NaOH solution (30 min)	extract from water (30 min)	extract from water (7days)
Si	m	m	m
Na	17000	4800	3900
Ca	2800	27000	3500
Mg	2600	33000	2500
Al	2100	1500	390
Ti	71	1200	70
Remarks	"m" cannot measure because of eluting much more, unit (ppm)		

Table 4 The results of ICP analysis of blast-furnace slag

	extract from NaOH solution (30 min)	extract from water (30 min)	extract from water (7days)
Si	4300	1800	7800
Na	16000	27	27
Ca	21000	13000	31000
Mg	210	3200	990
Remarks	unit (ppm)		

observed. ICP analysis of blast-furnace slag powder, as presented in Table 4, indicates the elution of large quantities of Ca. In the initial stage of the reaction, the eluted Na and Ca atoms become ionised and combine with hydroxide ions to form sodium hydroxide and calcium hydroxide. Because of the creation of sodium hydroxide, the liquid phase shows high pH, and the amorphous blast-furnace slag powder is stimulated and activated. Furthermore, calcium hydroxide made from the blast-furnace slag powder participates in a hydration reaction with silica in high-alkaline surroundings to create calcium silicate hydrate (C-S-H) [4]. It is believed that filling voids in soil structures with calcium silicate hydrate condenses and cures the soil structures. Furthermore, the soil surface is activated by alkaline ions created during the initial stage of the reaction, and Si eluted from the silica-based solidification material creates a silica colloid. It is considered that silica colloid fills the voids in soil structures to adhere to activated soil surface, and cure. It is further supposed that the long-term strength of the silica-based solidification material is due to a pozzolanic reaction.

4. TEST DESCRIPTION

4.1 Sample soil and mixing condition

A list of test cases is shown in Table 5. The mixture of the silica-based solidification material and blast-furnace slag is used as a solidification material. The silica-based solidification material is white and powdery and has a SiO_2 content of approximately 50 %, a density of 2.56 g/cm^3 and a grain size of 20 to 100 μm.

The slag consists of blast-furnace slag powder. The compounding ratios of a silica-based solidification material (H) and blast-furnace slag powder (SL) are SL/H = 5, 10 and 15 by weight. For comparison, a powdery cement-based solidification material (C) used in high-pressure injection mixing methods is also tested. Each solidification material is used with slurry. The compounding ratio of water (W) and a solidification material (M) is W/M = 130 %. In the case of the powdery cement-based solidification material, M = C. In the case of the mixture of the silica-based solidification material and blast-furnace slag, the volume of the solidification material is the total volume of each component (M = H + SL).

Sandy and clayey materials are selected for the test. The sandy material is Toyoura silica sand (σ = 2.367 g/cm^3), and its water content, w, is adjusted to w = 10 %. The clayey material is Tochi-cray, made in Tochigi prefecture, (σ = 2.724 g/cm^3, w_L = 34.0 %, w_p = 17.0 %, I_p = 17.0), and its water content is adjusted for over 12 hours to be w = 40 %. The compounding ratios of the soil material (S) and solidification material (M) are set to S/M = 2.0 and 1.5 by volume.

4.2 The testing method

In order to confirm the strength characteristics of improved ground, a compression test is conducted. Test pieces are created using a mould of diameter 50 mm and height 100 mm. The uniaxial compression test is conducted after the test pieces are cured for 1, 3, 7, 28 and 56 days.

5. THE TEST RESULTS AND DISCCUSIONS

5.1 Differences between soil materials

The relationship between compressive strength and age for each solidification material is shown in Fig. 2. In the case of the powdery cement-based solidification material, the sandy material case has a higher strength than the clayey material case. This behavior accords with what has been observed in the literature [5]. On the other hand, in the case of the silica-based solidification material, clayey material cases have higher strengths than sandy material cases after approximately 20 days. Because the grain size of Tochi-cray is very small, its specific surface area is large. Furthermore, Tochi-cray contains soluble SiO_2 and Al_2O_3 eluted from the clay mineral. Therefore, the adhesion effect of silica is greater in clayey materials than in sandy materials. Because increased strength also occurs

Table 5 List of test cases

No.	solidification material				compounding conditions			
	SL/H			C	ground material		S/M	
	5	10	15		cray	sandy	2.0	1.5
1	x				x		x	
2	x					x	x	
3		x			x		x	
4		x				x	x	
5		x			x			x
6		x				x		x
7			x		x		x	
8			x			x	x	
9				x	x		x	
10				x		x	x	
11				x	x			x
12				x		x		x

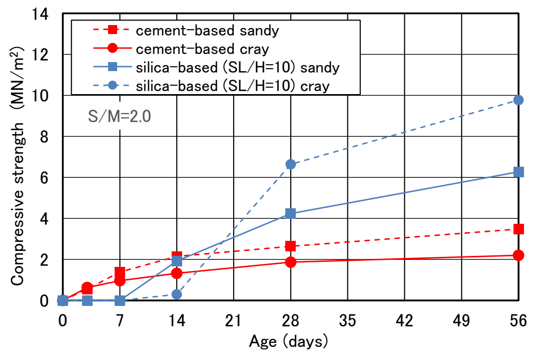

Fig. 2 Change of compressive strength as a function of time for each solidification material

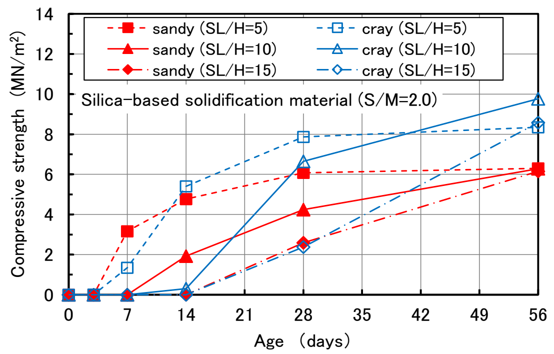

Fig. 3 Comparison by compounding ratio

because of a pozzolanic reaction, Tochi-cray has a higher strength than sandy materials.

5.2 Long-term strength

The relationship between compressive strength and age under each of the compounding ratios is shown in Fig. 3. In the case of the powdery silica-based solidification material, a strength increase is found after 28 days. It is believed that the silica-based solidification material includes more silica, alumina and calcium hydroxide than the powdery cement-based solidification material, because the pozzolanic reaction advances briskly after 28 days, increasing strength. Furthermore, it is believed that the pozzolanic reaction would continue to increase strength after 56 days.

5.3 Efficiency of the delay of strength development

As shown in Fig. 2, in the case of the powdery silica-based solidification material, the strength increases with age even after 28 days, but the increment is small. On the other hand, strength development of the silica-based solidification material is slower than that of the powdery cement-based solidification material, and the test pieces do not stand without support until 7 or 14 days later. Considering the solidification mechanism of the powdery cement-based solidification material, hydration occurs immediately and strength increases slowly. However, because the silica-based solidification material needs time to develop latent hydraulic properties of blast-furnace slag and for silica to adhere between soil particles, the test pieces do not stand without support until 7 or 14 days after their creation.

6. CONCLUSIONS

In this study, the authors developed a silica-based solidification material and clarified its solidification mechanism. The following results were obtained.

(1) From XRD analysis, the blast-furnace slag powder was found to be amorphous and caused by curing mixture with silica-based solidification material and a blast furnace slag powder.
(2) ICP analysis showed that, during the initial stage of the reaction, Na and Ca were eluted from the silica-based solidification material, causing the pH of liquid phase to increase and activating the blast-furnace slag powder. Si becomes silica colloid, and an adhesion effect occurs between soil particles.
(3) ICP analysis also showed that large quantities of Ca were eluted from the blast-furnace slag powder, creating $Ca(OH)_2$ and C-S-H and causing hardening through areaction with Si.
(4) Because the adhesion of the effect between soil particles due to silica and the development of long-term strength due to pozzolanic reactions, clayey materials have higher strengths than sandy materials, and effect of the improvement is large.
(5) The silica-based solidification material undergoes a brisk pozzolanic reaction due to the inclusion of much silica, alumina and calcium hydroxide. The increase in strength is large after 28 days, and continues even after 56 days.
(6) Strength development of the silica-based solidification material is slower than that of the cement-based solidification material, because there is efficiency of delay, it is possible to apply to ground improvement method to need overlap.

This study indicates that the silica-based solidification material has excellent delay efficiency but that the delay in strength development is a general problem. The reaction is promoted by increasing the amount of silica-based solidification material. It may be possible to advance strength development, but the exact compound involved in early strength development is unclear, making this a problem for future research.

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