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Development of Filler for Underground Cavities "SMART GROUT™" Using Granulated Blast Furnace Slag†

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Abstract:

The liquefaction and consolidation cause ground subsidence and underground cavities. Because the cavities can be a possible cause of troubles such as caving or declination of the building, they are usually filled with some kind of filler. JFE Steel developed the filler for underground cavities called "SMART GROUT™" using granulated blast furnace slag. By a laboratory mixing test and a field test using actual equipment, it was clarified that "SMART GROUT™" could be pumped out more than 200 m and cast in the water firmly.

1. Introduction

Subsidence due to consolidation of soft ground and ground liquefaction due to earthquakes can cause underground cavities between building foundations or roadways and the ground. Because these cavities can also cause damage in the form of caving of the ground surface and declination of buildings, they are usually filled by injecting a filling material[1)]. Injection of fillers through inlets provided in the base slab is widely used, as this method has the advantage that recovery measures can be implemented without large-scale excavation. Filling materials must have good fluidity during casting and strength properties equal to those of the ground after casting. Conventionally, sand and a cement-based solidification agent were used as the main materials of fillers. However, in order to reduce consumption of natural resources and decrease environmental loads, use of recycled materials had been demanded. Therefore, JFE Steel developed the filler for underground cavities called "SMART GROUT™" using granulated blast furnace slag, which is a type of steel slag.

As granulated blast furnace slag has virtually the same grain size distribution as natural sand, it can be used as an aggregate for fillers. This slag also has the property of latent hydraulicity, that is, it forms hydrates by reaction with water in response to the stimulant action of alkalis, etc. Since this contributes to strength development, a reduction in the mixture proportion of cement and a decrease in environmental loads by substitution of recycled slag for natural materials can be expected.

This paper describes the basic properties of "SMART GROUT™" and its applicability at the construction site.

2. Performance Requirements for Cavity Filling Material

As shown in **Fig. 1**, when filling a cavity under a base slab, a filler which has been pumped from a nozzle is injected into the cavity through an inlet provided in the slab. The following performance is required in fillers for cavities under foundations.

(1) Material strength equal to that of the ground
(2) Fluidity to enable long-distance pumping and filling of the cavity without voids
(3) Castability in water, assuming cases in which

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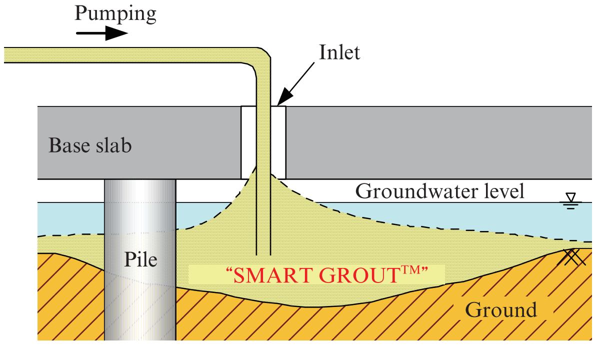

Fig. 1 Schematic view of casting “SMART GROUT™”

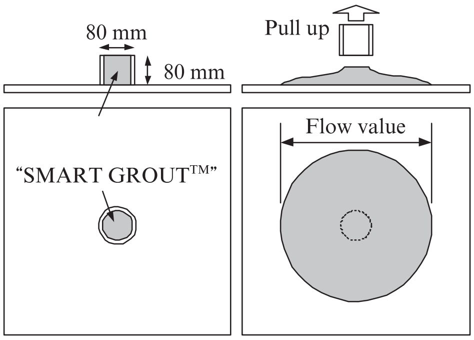

Fig. 2 Flowing test method

Photo 1 Overview of flow test

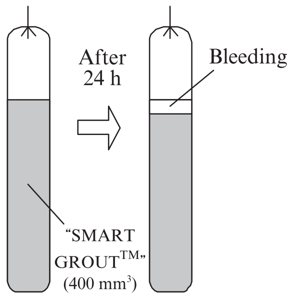

Fig. 3 Bleeding test method

groundwater exists in the cavity

Performance requirements for the strength properties of fillers will differ, depending on design concept. However, in the present case, strength was set at the same level as that of the ground (approx. 0.1–0.5 N/mm² after curing for 28 days). This was adopted because material strength equal to that of the original ground is adequate for recovery of a cavity, and an adequate subgrade reaction for the base slab and piles can be obtained. On the other hand, if the strength of the filler is excessive, adhesion with the foundation piles will occur. If the filler adheres to the piles, and further subsidence then occurs, a cavity will develop between the filler and the underlying ground, and in this case, recovery will be difficult. Adhering filler also places loads on piles, necessitating a restudy of the bearing capacity of the piles and the stresses generated in the piles themselves. Moreover, it is also desirable that the strength of the filler be similar to that of the ground in order to avoid adverse effects on buried pipelines, etc.

When casting a filler, the filler must have sufficient fluidity to flow smoothly through the pumping pipe from the mixing plant to the inlet location and then fill the cavity completely without voids. Conversely, if fluidity is set too high, there is a possibility that the materials may segregate, and blockage of the pumping pipe and decreased performance during filling are concerns. Fluidity is confirmed by the flowing test shown in **Fig. 2** and **Photo 1**, and resistance to segregation is confirmed by the bleeding test in **Fig. 3**.

Because the water table is near the surface at locations that are prone to subsidence due to consolidation and liquefaction, groundwater frequently exists in cavities. Considering casting at locations of this type, the filler materials must not segregate in water, and the unit weight of the filler must be greater than that of water so as to enable filling without floating on the surface of the groundwater.

Referring to the performance requirements for micro-sand air mortar[2), which is an existing technology, the performance requirements and quality test items for

Table 1 Performance requirements and quality test items for “SMART GROUT™”

Item		Performance requirement	Quality test item	Target value
(1)	Material strength	Same strength as ground Shall not adhere to piles	Unconfined compression strength	0.1 N/mm² or higher (28-day curing)
(2)	Fluidity	Long-distance pumping and filling without voids possible	Flowing test	210 mm or more
(3)	Casting in water	Casting possible without material segregation	Bleeding test	5.0% or less
		Filling possible without floating on water	Unit weight	1.0 g/cm³ or more

Table 2 Mixture proportion and test result

Mixture number	Mixture proportions (kg/m³)					Test results				
	Granulated blast furnace slag	Slag cement	Bentonite	Frothing agent	Water	Flow value (mm)	Bleeding (%)	Unit weight (kN/m³)	Compressive strength (N/mm²)	
									Curing for 7 days	Curing for 28 days
1	958	107	18	0.63	353	218	6.3	1.48	0.114	0.269
2	689	77	26	0.50	510	344	21.6	1.71	0.125	0.403
3	705	46	46	0.50	507	244	0.4	1.33	0.055	0.229
4	622	34.5	34.5	1.00	346	211	0.0	1.01	0.026	0.069

"SMART GROUT™" were set as shown in **Table 1**, and the mixture proportion for satisfying those performance requirements was studied in laboratory tests.

3. Study of Mixture Proportion by Laboratory Tests

The materials used in the mixture were granulated blast furnace slag (Particle size adjusted to 5 mm or less; **Photo 2**) as the aggregate, blast furnace slag cement (type B) as the solidification agent, bentonite as a segregation-reducing material, a frothing agent to improve workability by reducing weight, and water.

Figure 4 shows an example of the grain size distributions of the granulated blast furnace slag used here and manufactured sand (crushed sand) for use as a fine aggregate in concrete[3]. From Fig. 4, it can be understood that the grain size distribution of the granulated blast furnace slag is in the same range as that of sand used as a fine aggregate in concrete. However, the fluidity of the granulated blast furnace slag is lower than that of sand due to the angular shape of the slag, and as a result, the slag tends to segregate. Therefore, bentonite was used to prevent segregation. As bentonite is a clay mineral, it increases the viscosity of the filler, thereby reducing segregation of the materials. Furthermore, in order to improve fluidity, air bubbles produced by the frothing agent are mixed in "SMART GROUT™" to reduce its weight and improving pumpability.

Table 2 shows the main mixture proportions used in the laboratory tests and the test results. Here, referring to the mixture proportions of existing cavity fillers for use under slabs[1,2], the normal aggregate was replaced with granulated blast furnace slag in Mixture Nos. 1 and 2. Then, in Mixture Nos. 3 and 4, the blending proportions of the blast furnace slag cement and the frothing agent were adjusted based on the results with Mixture Nos. 1 and 2. Since the test results showed that Mixture No. 3 satisfied all the target values for material strength, fluidity, and casting in water, this mixture proportion was adopted as the standard mixture. On the other hand, as the 28-day strength of the developed mixture was 2–4 times greater than its 7-day strength, its strength development was large in comparison with that of general cement-based solidification agents. This is attributed to the fact that the latent hydraulicity of granulated blast furnace slag is slower than the hydration reaction of cement.

Photo 2 Granulated blast furnace slag

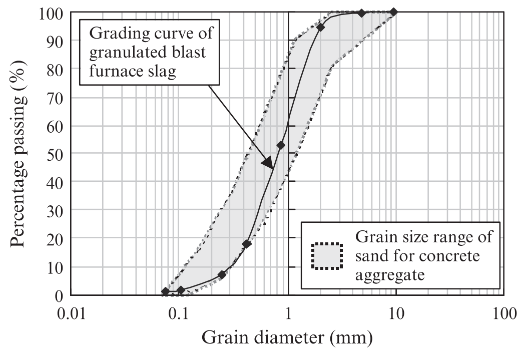

Fig. 4 Grain size distribution of granulated blast furnace slag

4. Verification of Workability by Laboratory Tests

4.1 Visualization of Fluidity

In order to confirm the fluidity of "SMART GROUT™," a model simulating an underground cavity was prepared in a water tank, and a visualization test in which "SMART GROUT™" was made to flow into the cavity was performed. The dimensions of the tank were width 300 mm × height 300 mm × length 1 200 mm. An open space with a height of 50 mm was provided as the cavity. Silica sand was laid on the tank bottom assuming dry ground. As shown in **Photo 3**, "SMART GROUT™" prepared with mixture proportion No. 3 was poured in

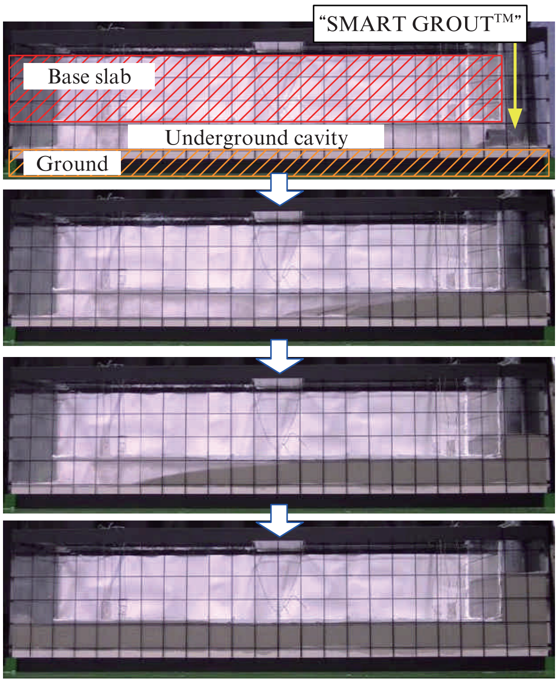

Photo 3 Visualization of fluidity

from the right side, and flowed through the cavity to a distance of 1 000 mm and filled the cavity without voids.

4.2 Evaluation of Required Casting Time and Fluidity

In site construction, a time lag may exist between mixing and injection, for example, when the mixing plant and the injection site are separated by some distance, etc. Therefore, in order to investigate the change in fluidity over time, flow values with and without agitation after mixing were compared using Mixture No. 3 in Table 2 without mixing air bubbles. **Figure 5** shows the relationship between the curing time and the flow value with and without agitation. Without agitation, the flow value immediately after mixing was 196 mm, but this decreased to 90 mm in a flow test performed after passage of 150 min. Because "SMART GROUT™" is mixed using blast furnace slag cement (type B), it is considered that the hydration reaction proceeds as time passes after mixing, and as a result, fluidity decreases. On the other hand, when agitation was continued after mixing, there was no decrease in the flow value up to 120 min after mixing. From this, it is considered that casting can be performed in a condition that maintains the same fluidity as immediately after mixing, if "SMART GROUT™" is transported by a cement mixer while continuing mixing in the truck, and air bubbles are then added to the mixture at the site.

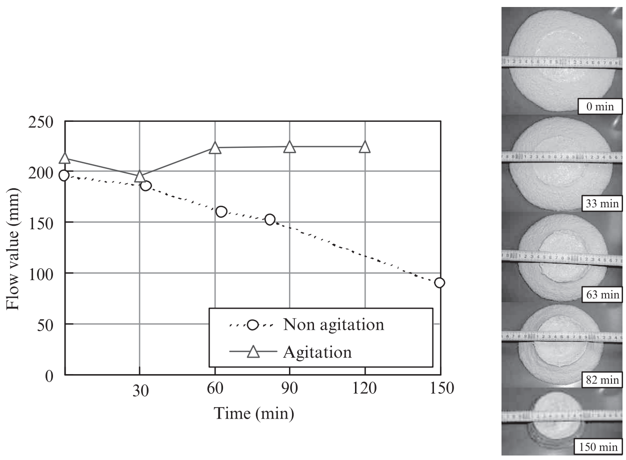

Fig. 5 The relation between curing time and flow value

4.3 Verification of Casting in Water

In order to confirm the castability of "SMART GROUT™" in water, a visualization test was performed by pouring "SMART GROUT™" into a tank filled with water. The tank dimensions were width 300 mm × height 300 mm × length 600 mm. The water was colored with ink so that the height was 200 mm, and "SMART GROUT™" was poured into this colored water. Immediately after pouring, a phenomenon in which the mixed

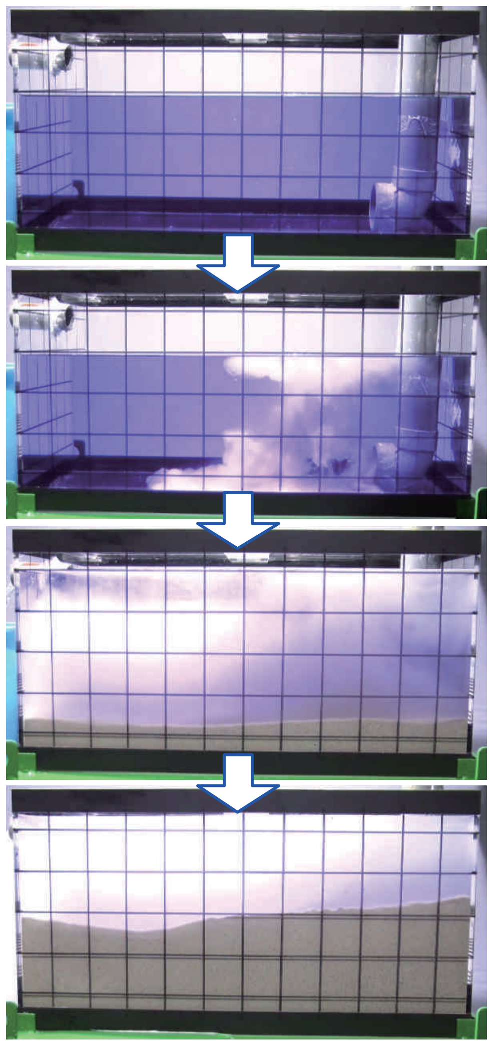

Photo 4 Visualization of casting in water

air bubbles separated and floated to the surface was observed, causing the water to be cloudy. However, when the pouring rate was stable, a situation in which the tank was filled from the bottom while "SMART GROUT™" pushed out the water was observed. Thus, it was found that casting in water is possible without segregation of the materials (**Photo 4**).

A core sample of "SMART GROUT™" which had been cured in water for 28 days after casting was taken, and an unconfined compression test was performed. The result was 0.149 N/mm^2, which was a decrease to approximately 60% of the unconfined compression strength of 0.229 N/mm^2 measured with a specimen cured in air. In spite of this decrease, the result satisfied the target strength of 0.1 N/mm^2.

5. Site Casting Test Using Actual Plant

Casting tests were performed using an actual plant in order to confirm the site mixability, pumpability, and castability in water of "SMART GROUT™." **Figure 6** and **Photo 5** show the arrangement of the equipment and an overview of the plant. The mixture was performed by choosing mixture proportion No. 3 in Table 2, and a total of 13 m^3 was mixed with a 1 m^3 batch-type mixer. As the work sequence, first, the granulated blast furnace slag, slag cement, bentonite, and water were charged

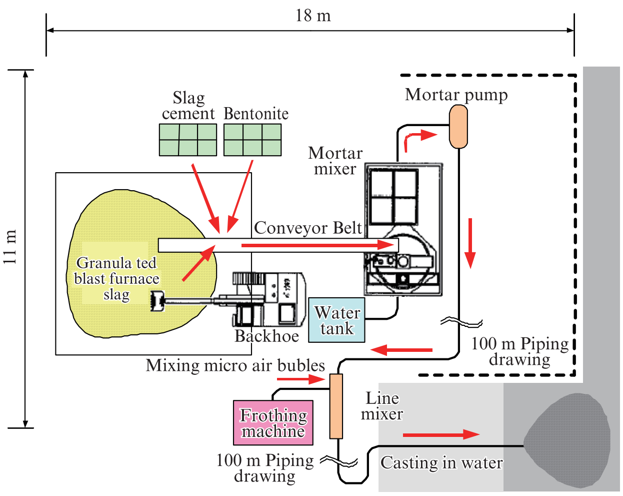

Fig. 6 Layout of mixing plants

Photo 5 Overview of mixing plants

Photo 6 Casting in water

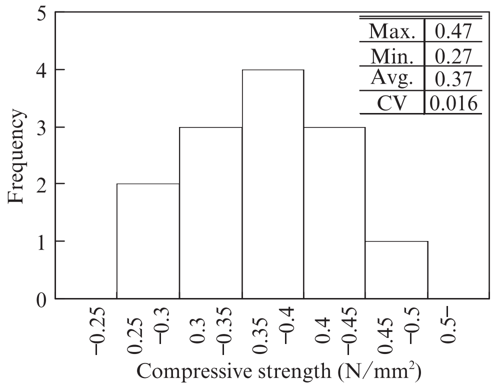

Fig. 7 Dispersion of compressive strength

into the mixer and mixed to a mortar-like condition, this mixture was pumped 100 m with a squeeze pump, air bubbles were prepared using a frothing machine and then added to the mixture using a motorized line mixer, this mixture was pumped an additional 100 m, and finally, casting was performed in water. A maximum pumping distance of 200 m was possible by successfully mixing air bubbles by setting up the line mixer at the bubble mixing position. The fact that casting in water is possible was also confirmed, as shown in **Photo 6**.

Samples of "SMART GROUT™" were taken after pumping, and an unconfined compression test was performed. The results are shown in **Fig. 7**. Although a maximum variation of approximately 2 times could be seen in the unconfined compression strength, the results satisfied the target performance in all cases, and homogenous mixing was confirmed.

6. Conclusion

"SMART GROUT™" is a cavity filling material using granulated blast furnace slag, and has the following features.

(1) Because "SMART GROUT™" uses granulated blast furnace slag, which is a byproduct of the steel manufacturing process, environmental loads are reduced and material costs can be held down.

(2) The latent hydraulicity of granulated blast furnace slag makes it possible to reduce the mixture proportion of cement.

(3) The unit weight of the material can be controlled by changing the amount of air bubbles produced by the frothing agent.
(4) Use of bentonite in the mixture prevents segregation of the materials and enables casting without segregation even in water.

Laboratory tests were performed to study the mixture proportion of "SMART GROUT^{TM}" for satisfying the performance requirements, confirm the change in fluidity over time, and confirm the condition of segregation during casting in water. Pumpability and casting in water were confirmed in casting tests using an actual plant. As results, a maximum pumping distance of 200 m was possible, and casting could be performed in water without segregation.

During the Great East Japan Earthquake of 2011, ground liquefaction occurred in many areas, and underground cavities are also said to have formed[4]. As a result, requests for recovery work are expected to increase in the future.

"SMART GROUT^{TM}" is a "construction method that reduces effects on environment," as use of cement and natural sand can be reduced in comparison with the conventional method by utilizing granulated blast furnace slag, which is a byproduct of the steel manufacturing process. As excellent results were achieved with this eco-technology, the authors wish to propose "SMART GROUT^{TM}" as a construction method that should be adopted in recovery work.

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