

1. Enhancing the sustainability and efficiency of trapezoidal CSG dams An innovative approach using nonstandard fly

Enhancing the sustainability and efficiency of trapezoidal CSG dams: An innovative approach using nonstandard fly ash

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ABSTRACT: In this study, the feasibility of using fly ash (coal ash) as a partial substitute for cement material for the trapezoidal cemented sand and gravel (CSG) dam, is examined to reduce the environmental impact and effectively use resources during construction. A trapezoidal CSG dam is composed of rocky material mixed with cement and water as the dam body material. This rocky material is referred to as CSG material. Because of the shapes of the cross-sections of trapezoidal CSG dams, the stresses generated are small (a few MPa). With the appropriate mixing ratio, the decrease in strength at an early age may be acceptable due to the inclusion of fly ash. Conversely, the use of fly ash should reduce the risk of temperature cracking due to the reduction in hydration heat generation inside the dam body and the increase in long-term strength due to pozzolanic reactions, suggesting that the proactive use of fly ash is worthwhile. The fly ash used in this study is not the Japanese Industrial Standard (JIS) Class II fly ash currently used for concrete but instead a non-JIS product. Fly ash is blended into the outer mixture of cement. The test results are as follows. (1) Compared to those of the mixture without fly ash, the mixture with fly ash in the outer mixture tends to exhibit small changes in the CSG density and strength over time, confirming that this mixture is effective. (2) Of the formulations with fly ash, those with 200 kg/m³ of fly ash show relatively high CSG strength. In the Naruse Dam, the CSG strength of 100 kg/m³ of cement with material D (a mixture of dam site terrace deposits and crushed rock material from the Akataki quarry site) without fly ash is 2.5 N/mm². Furthermore, the mix with fly ash in the outer mixture has a strength approximately 2 to 3 times greater than the CSG strength. However, test results at 91 days of age are considered to reflect the physical properties of fly ash. Additional testing is desirable to confirm the long-term strength development that reflects the inherent chemical properties of fly ash.

1 INTRODUCTION

In trapezoidal CSG (cemented sand and gravel) dams, rocky material mixed with cement and water is used as the body material. This rocky material is called CSG material. In addition to crushed rock, riverbed sand and gravel, and terrace sediments are used either individually or blended with the other materials. Unlike concrete aggregates, CSG material, which is quarried on site, is not generally classified, graded, or washed. In the Naruse Dam in Akita Prefecture, which is being constructed as a trapezoidal CSG dam, the CSG material is a blend of crushed rock and terrace sediments. Due to the presence of smectite clay minerals in terrace sediments, early setting occurs, and changes over time after CSG mixing are large, making it difficult to stably achieve the prescribed compaction density (Hanakago et al., 2022). As a countermeasure, a super retardant is used, improving the workability and affording stable quality CSG. In this study, the possibility of utilizing coal ash (fly ash) as a substitute for cement material is investigated for Naruse Dam to reduce its environmental impact and effectively utilize resources in construction. It is known that fly ash generated from thermal power plants has not been effectively utilized as a recycled resource, and it has been disposed of as an industrial waste. In addition, the policy of Akita Prefecture (municipal government), which is where the Naruse Dam is located, is to promote the effective use of fly ash for concrete products. Additionally, the Guideline for the Promotion of Environmental Goods Procurement (MLIT, 2005) promotes the use of fly ash for mass concrete, such as dam construction, where early strength is not needed. Notably, there are regional differences in supply conditions. The trapezoidal cross-section of a CSG dam results in a small stress of only a few MPa. With the appropriate mixing ratio, the reduction in strength at the early age of the material due to the existence of fly ash may be acceptable. Conversely, the use of fly ash should decrease the risk of temperature cracking due to the reduction in hydration heat generation inside the dam body and the increase in long-term strength due to pozzolanic reactions, suggesting that the proactive use of fly ash is worthwhile. Therefore, the possibility of effectively utilizing fly ash in trapezoidal CSG dams is investigated. The fly ash used in this study is not the Japanese Industrial Standard (JIS) Class II fly ash currently used for concrete but rather a non-JIS standard fly ash, with the aim of using it for CSG. The CSG from the Naruse Dam is mixed with a super retardant because the presence of smectite causes premature setting of the CSG. Therefore, an objective of this study is to examine whether the use of fly ash can alleviate premature setting.

2 LABORATORY TEST

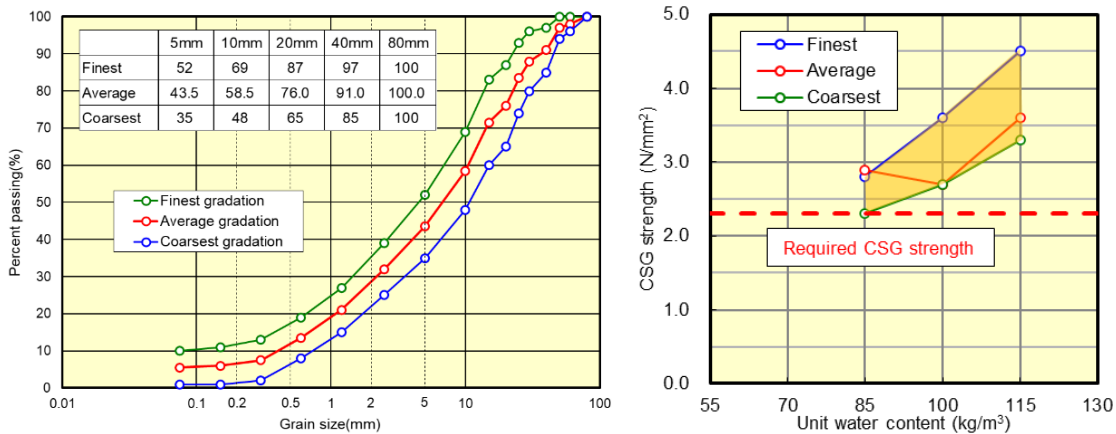
2.1 Test material preparation

Gradation tests of the CSG materials obtained from different locations in the material quarrying site are conducted to determine the coarsest and finest gradations. The gradation of the CSG material used is distributed between the coarsest and finest values, as shown in Figure 1. Then, mixing tests with varying unit water contents are conducted to clarify the allowable range of water content for the coarsest and finest gradation curves. Cylindrical specimens are prepared using the coarsest gradation and finest gradation CSG material and with a constant cement content and variable water content to test the strength of the CSG in a laboratory. The strength of the CSG is tested using an unscreened full-size CSG with a maximum particle size of 80 mm. Therefore, in this test, large-scale specimens with columnar shapes 300 mm in diameter and 600 mm in height are used. The specimens are compacted by an electric-powered hammer, which can achieve the same density as the on-site CSG density. The range of the unit water content is selected from the abovementioned allowable range of unit water content while considering the execution controllable range. The shaded diamond-shaped portion in Figure 1(a) is set by using straight lines of the unit water content range for execution and the strength curves of the coarsest gradation and finest gradation. Finally, the lowest strength in this diamond-shaped region is set as the CSG strength (Fig. 1(b)) (JDEC, 2012). During the execution stage, the strength of the CSG material between the coarsest and finest gradations and within the range of unit water content is ensured to be higher than the abovementioned CSG strength. Above mentioned characteristic is considered the diamond-shaped theory for setting CSG strength. The quality of CSG is controlled by this theory.

In the Naruse dam, the CSG material is a mixture of dam site terrace deposits and crushed rock material from the Akataki quarry site (Material D), with a unit cement content of 100 kg/m³ and a unit water

content of 125 kg/m³, which is the median value for a diamond shape. Standard specimens (ϕ 20 cm × h40 cm) are prepared to evaluate the density, strength, and change over time (compaction degree per elapsed time). The grain size distribution used is the coarsest gradation II, as shown in Figure 3. The coarsest gradation is revised to a slightly finer gradation based on the variation analysis of the grain size range of the CSG materials during the construction of the Naruse Dam. The coarsest gradation set at the laboratory test is referred to as coarsest gradation I, and the newly set gradation is referred to as coarsest gradation II.

In the test case where a super retardant is used, the addition rate is fixed at 2% for 100 kg/m³ of unit cement content. The non-JIS standard fly ash used in this study is selected and delivered as a product of inferior quality. Physically, the fly ash has a low bran value, and chemically, it has a high carbon content with a large amount of ignition loss. The reason for using the coarsest gradation II is that the CSG strength defined by the diamond shape is determined by the coarsest gradation II in most of the formulations. Thus, the properties are confirmed at the coarsest gradation II. In addition to the coarsest gradation II, the finest gradation is set separately for the Naruse Dam. The properties are confirmed by changing the grain size (#9 and #10) and unit water content (#10). The test cases are shown in Table 1. Notably, if fly ash is replaced by cement in the inner mixture, the test case involves the outer mixture because the fly ash reacts slowly and does not develop sufficient 91-day CSG strength, which is the required CSG strength. The concepts of inner and outer mixing are shown in Figure 2.



(a) Setting of gradation range.

(b) Diamond-shaped theory example.

Figure 1. Gradation range and diamond-shaped theory.

Table 1. Confirmation test in the laboratory (terrace deposit: crashed rock = 50:50 (Material D)).

#	Mixing apparatus	Unit powder amount		Unit water	Super retarder C x %	Curing	Particle size distribution	Remarks
		C	FA					
1			-		0			Basic
2			-		2			
3			100		0		Coarsest Gradation II	Outer mixing
4			100		2			
5	Pot mixer		200	125	0	Sealed curing 20 °C		
6			200		2			
7			300		0			
8			300		2			
9			200		0			
10			200	140	0		Finest Gradation.	

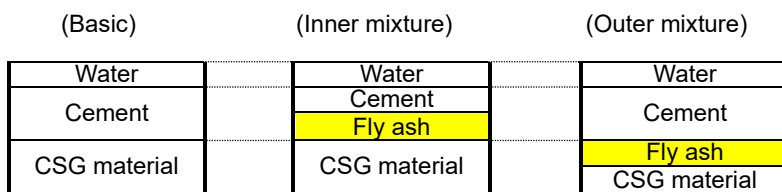
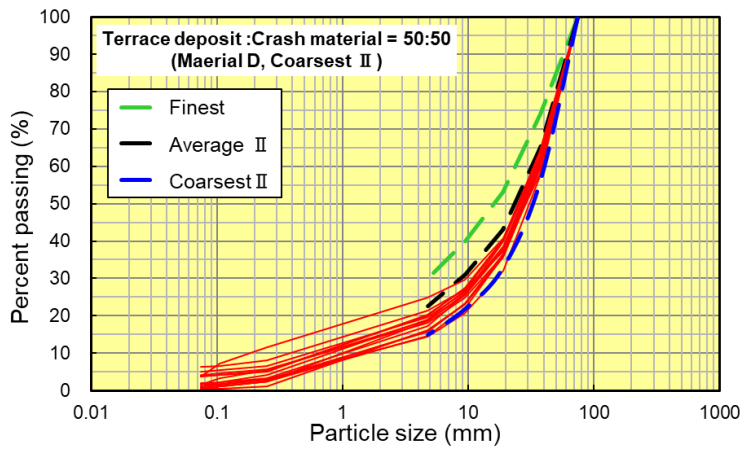


Figure 2. Concepts of the inner and outer mixture.

Figure 3 shows the setting of grain distribution of the blended CSG material used in this research and Figure 4 illustrates the flow of the test procedure.



Grain size (mm)	Coarsest gradation II		
	Terrace	Crushed	Composite
75.0	50	50	50
37.5	33	33	56
19.0	23	10	33
9.5	17	6	22
4.8	12	4	15

Figure 3. Setting of grain distribution of the blended CSG material.

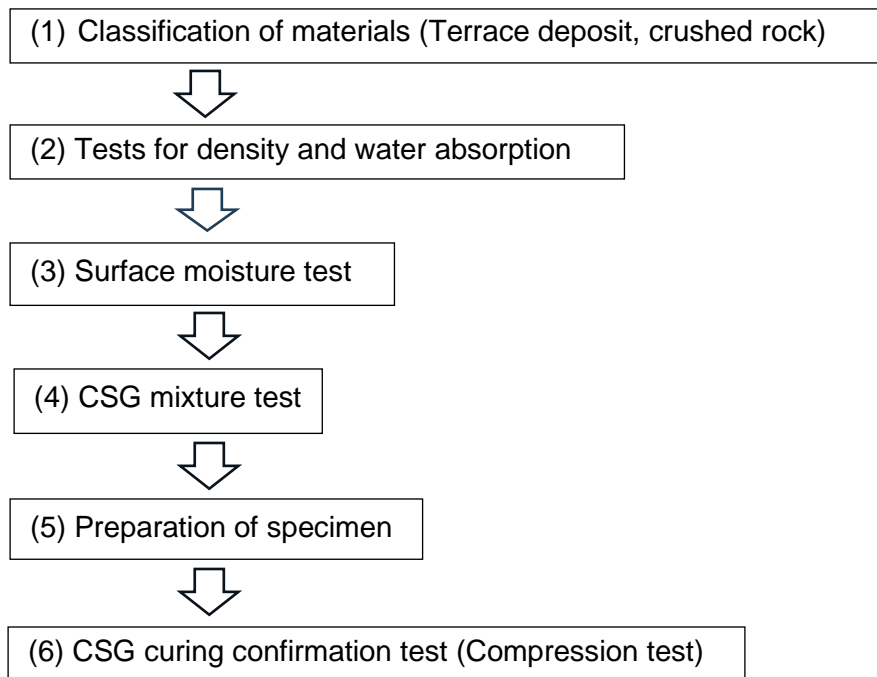


Figure 4. Test flow.

2.2 CSG testing materials

(1) Particle size adjustment and particle size test for the CSG material

As a preliminary preparation process for the mixing test, the dam site terrace deposits and the crushed

rock are sieved into five classes—80–40 mm, 40–20 mm, 20–10 mm, 10–5 mm, and 5–0 mm—using a sieving machine to produce the gradation specified in the diamond-shaped theory.

(2) Density and absorption tests

In parallel with the particle size test and classification work, density and water absorption tests are conducted for each particle range.

(3) Surface moisture ratio test

The day before the test, the classified CSG materials are sampled, weighed, placed in a dryer at 110 °C for 24 h. Subsequently, the samples are weighed after drying to measure the moisture content of each classified material. On the day of the test, the 10–5 mm and 5–0 mm samples are taken, weighed, dried in a microwave oven (600 W, 15 min), and further weighed after drying to determine the surface moisture content. Surface moisture ratios of 80–40 mm, 40–20 mm and 20–10 mm are tested using the results from the previous day.

(4) Mixing test for the CSG

The CSG is mixed in the laboratory using a pot mixer (200 ℓ). The CSG material and cement are weighed, placed in a mixer and mixed for 1 min. Afterward, water is added to cover the entire mixture, and it is mixed for 2 min. Then, the CSG is discharged. A total of 60 ℓ per batch is used for mixing.

(5) Preparation of specimens

In the CSG aging test, wet screened materials of mixed CSG on a 40 mm sieve are packed in a standard specimen. After 0 h, 2 h, 4 h, 6 h, and 8 h, the specimens are compacted for 30 s with a Bosch tamper. For the large specimen ($\phi 300$ mm \times h600 mm) for the compressive strength test, a void tube is set in the steel frame to make the large-scale specimen. After the CSG is discharged, the material is switched with a shovel, weighed per layer, and compacted in 4 layers. After adding the material to one layer, the material is poked 25 times with a pusher, and the material is tightened with an electric hammer in a set number of seconds. The compacted surface is scraped with a crowbar, and the next layer of material is added and compacted in the same manner. The top edge of the specimen is smoothed with a finishing plate, capped with cement paste, and sealed and cured in a curing room at 20 °C (not immersion curing) until the specimen reaches the specified age. The standard specimen ($\phi 150$ mm \times h300 mm) is first prepared in the same manner as the large-scale specimens and then sealed and cured in a curing room at 20 °C until the specimen reaches the prescribed age.

(6) Compressive strength test

Compressive strength tests are conducted on standard and large-scale specimens using a compressive strength testing apparatus with an external strain meter installed.

3 TEST RESULTS

3.1 *Change over time*

Figures 5 and 6 show the change over time in the CSG with fly ash. Figure 6 shows the surface conditions immediately after preparation for the large-scale specimens and after 2, 4, and 8 h for the standard specimens. Figure 5 shows a comparison of the test results with and without a super retardant. Overall, the densities of the specimens without the super retardant decrease with time. This trend indicates that the density achieved under the same compaction method decreases because the smectite clay minerals cause early setting and reduce the workability over time. The smallest change over time occurs without the super retardant, which is 200 kg/m³ of fly ash (#5). In fact, after 8 h, the surface of this specimen is more packed than the other specimens. In addition, the specimens with fly ash (#3, #5, and #7) exhibits smaller changes over time than those without fly ash (#1), confirming that the specimens can effectively improve workability. However, when 300 kg/m³ of fly ash is added (#7), the amount of fly ash increases, resulting in insufficient moisture content and a pasty appearance. As time passes, the moisture content decreases due to the hydration reaction, resulting in poor workability and a decrease in density. When fly ash is used at 200 kg/m³ (#9) for the finest gradation, as in #7, the lack of proper amount of water results in poor workability and a decrease in density over time. Furthermore, even when fly ash is added at 200 kg/m³

with the finest gradation and when the unit water content is increased to 140 kg/m^3 (#10), workability deteriorates and density decreases over time, probably due to insufficient water content, as in #7 and #9. A comparison of the results for a 2% addition rate of a super retardant is shown in Figure 5. The specimen with the super retardant (#6) shows almost no change over time. Of the specimens with a super retardant, fly ash at an outer mixing ratio of 200 kg/m^3 (#6) and 300 kg/m^3 (#8) has no change in density, suggesting that the addition rate of fly ash can be reduced.

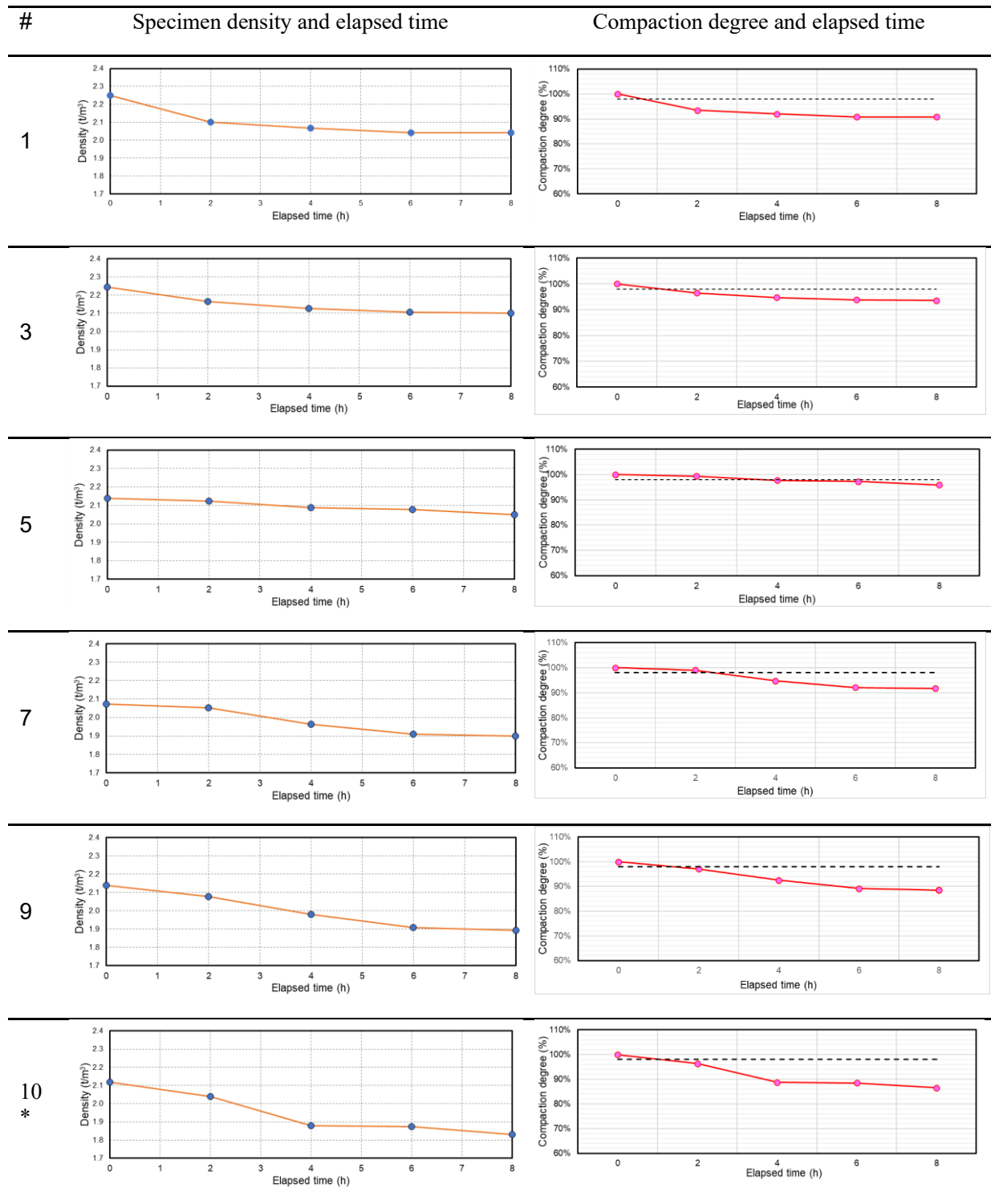


Figure 5(1). Fly ash aging tests (super retardant: 0%)*; 140 kg/m^3 of water.

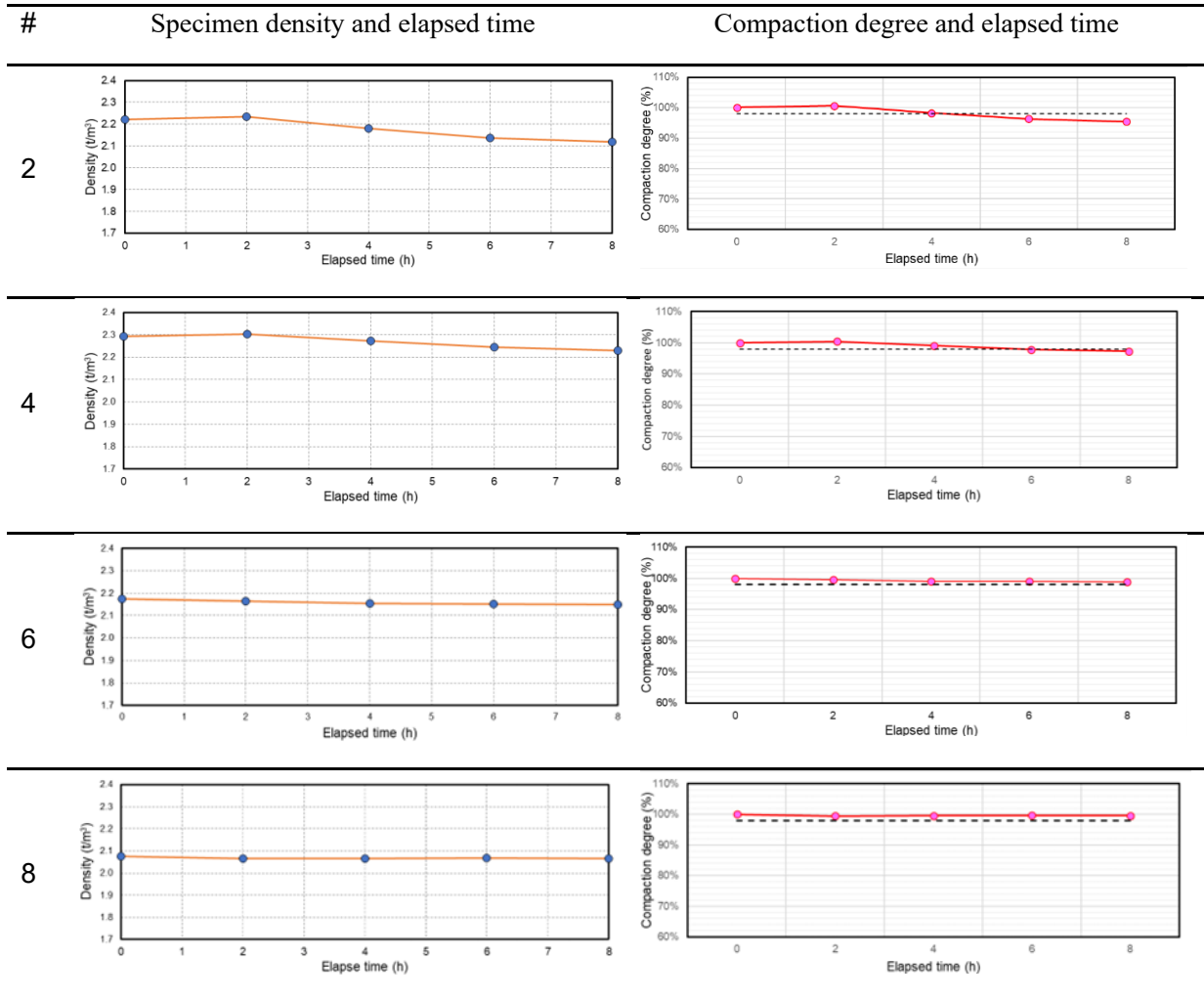


Figure 5(2). Fly ash aging tests (super retardant; 2%).

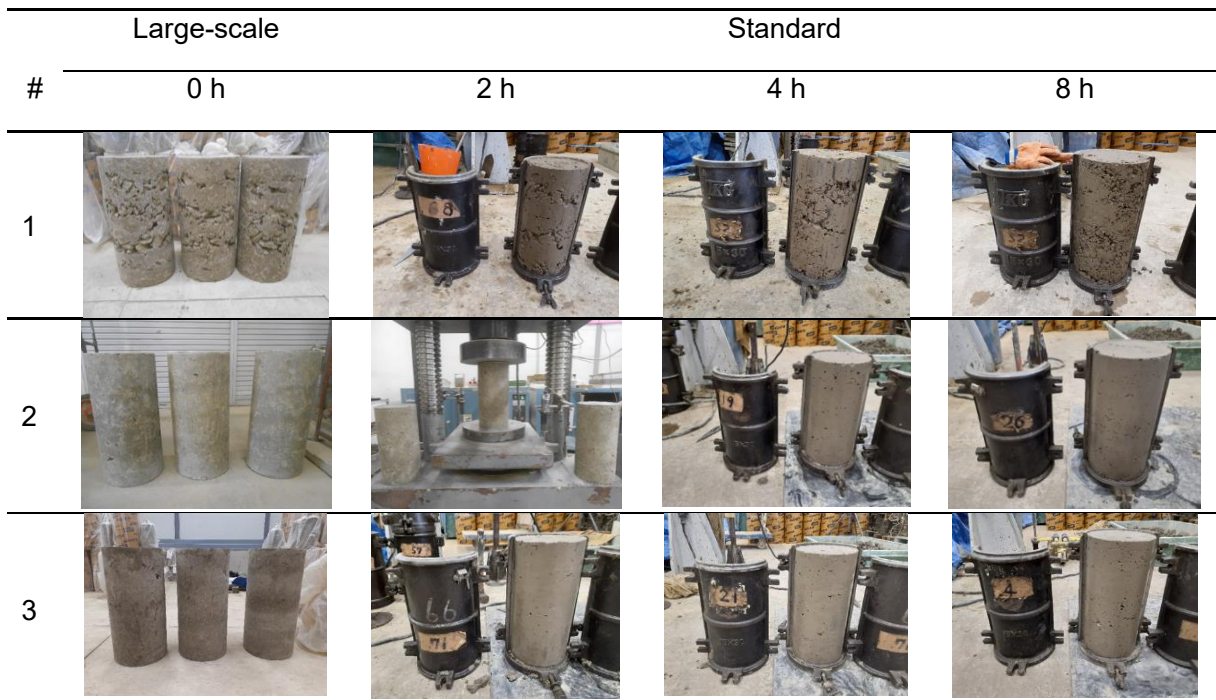


Figure 6. Specimen compaction for the fly ash aging test.

3.2 CSG strength

The strength test results for the CSG with fly ash are shown in Figures 7 and 8. Among the formulations (Fig. 7(a), #1 to #8) that include fly ash outside the JIS standard, the strength of the 200 kg/m³ formulation (Fig.7(b), #5 and #6) is high. The strength increases as the amount of fly ash increases from 0 kg/m³, and the strength decreases as the amount of fly ash exceeds 200 kg/m³. Compared to those without fly ash (#1 and #2), the blends with fly ash in the outer mixture (#3 through #8) have greater strength. This difference is thought to arise because the higher powder content results in a richer paste content, filling the voids in the CSG material and densifying the specimens. The strengths of the finest gradation specimens (#9 and #10) are lower than those of the coarsest gradation specimens. The CSG strength of Material D (a mixture of dam site terrace deposit and crushed rock material from Akataki quarry site) with 100 kg/m³ of unit cement is 2.5 N/mm², and the blending with fly ash in the outer mixture is approximately 2 to 3 times greater than its CSG strength in previous research. This finding suggests that it is possible to reduce the amount of cement.

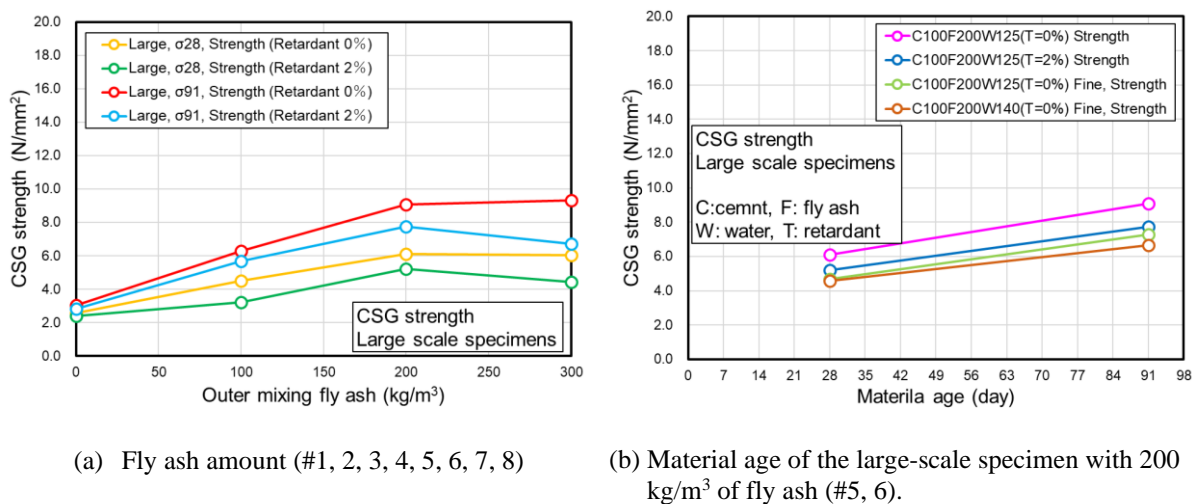


Figure 7. Relationship between the fly ash amount and CSG strength (coarsest gradation II).

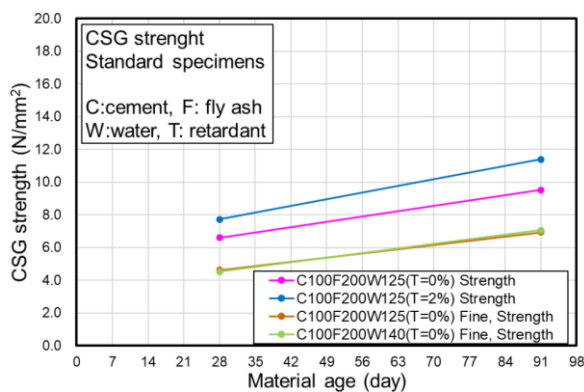


Figure 8. CSG strengths of standard specimens with 200 kg/m³ of fly ash (#5, 6).

4 COMPARISON OF THE INNER AND OUTER MIXTURES

Figures 9–11 show comparisons of the tests conducted in 2018 in which fly ash is added as an inner mixture of the unit cement amount and the tests conducted in this study in which fly ash is added to the outer mixture. For the inner mixture, the strength decreases as the amount of fly ash replacement increases, as shown in Figure 9. The elongation of the 28-day strength is approximately 1.5 at the 91-day strength,

except for the 70% fly ash replacement ratio. In addition, a slight elongation of strength is observed at 30% and 50% fly ash replacement ratios at the 182-day strength.

For the outer mixture, as shown in Figure 10 for the standard specimen, the strength increases as the amount of fly ash added increases. However, there is no significant difference in strength between 100 and 300 kg/m³ when the amount of fly ash added increases. The elongation of the 91-day strength is approximately 1.5, which is the same as that of the inner mixture. Conversely, in the large-scale specimens shown in Figure 11, the increase in strength becomes more pronounced as the amount of fly ash added increases. However, the strength plateaus at 200 kg/m³. According to the results of the present study, the addition of fly ash should have a positive effect. The test results approaching a 91-day strength are considered to reflect the physical properties of fly ash, and separate tests are desirable for investigating the long-term strength, which is an inherent property of fly ash.

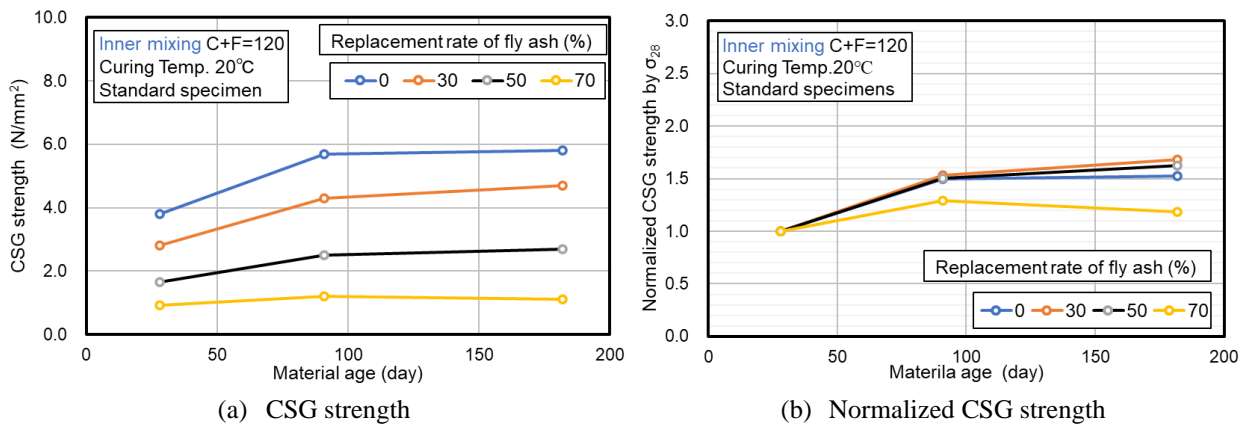


Figure 9. CSG strengths of standard specimens with fly ash and an inner mixture (previous research).

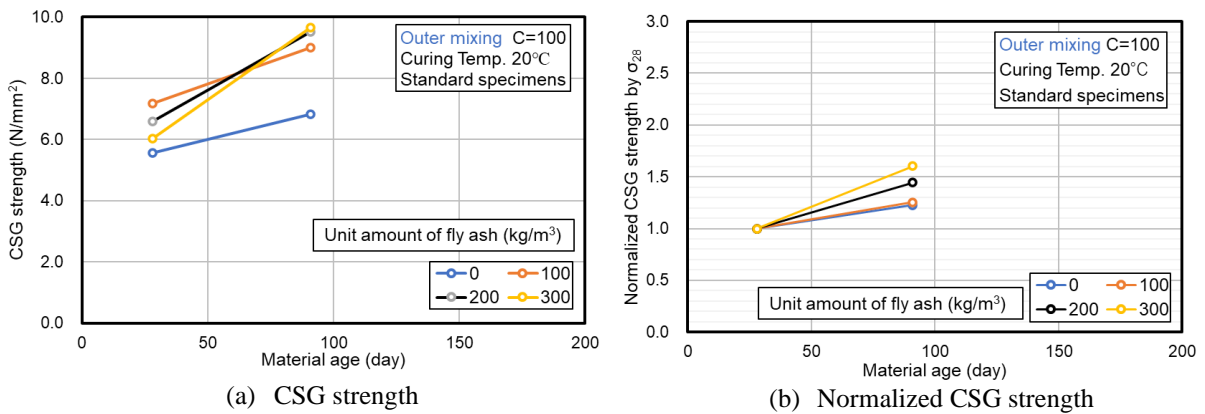


Figure 10. CSG strengths with fly ash and an outer mixture (standard specimens, #2, 4, 6, 8).

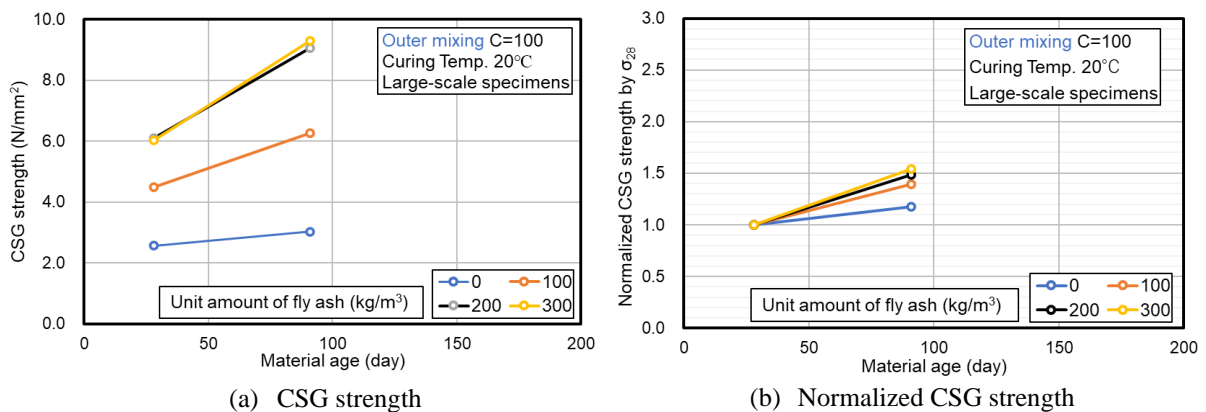


Figure 11. CSG strength with fly ash and outer mixture (large-scale specimens, #2, 4, 6, 8).

5 CONCLUSIONS

In this study, the feasibility of mixing non-JIS standard fly ash into a CSG dam was investigated, and the following conclusions were obtained.

- 1) The specimen without the super retardant exhibited the smallest change over time at 200 kg/m³. After 8 h, the surface of the specimen was more packed than that of the other specimens. The specimen with fly ash in the outer mixture tended to have a smaller change over time than the one without fly ash, confirming that it was effective.
- 2) Of the specimens with fly ash in the outer mixture, the specimen with 200 kg/m³ of fly ash exhibited greater CSG strength. The CSG strength with 100 kg/m³ of unit cement with Material D at Naruse Dam was 2.5 N/mm², and the CSG strength with the fly ash from the outer mixture was 2 to 3 times greater. This finding suggested that it was possible to reduce the amount of cement.

The test results for a 91-day strength could reflect the physical properties of fly ash, and a separate test could be desirable for investigating the long-term strength, which is an inherent property of fly ash.

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