- Technical Paper -

MECHANICAL PROPERTIES OF RECYCLED GLASS FINE AGGREGATE MORTAR MIXED WITH MINERAL ADMIXTURES UNDER ASR CONDITIONS

Hamin EU[*1], Gyuyong KIM[*2], Sujeong PYEON[*1] and Jeongsoo NAM[*3]

ABSTRACT

The recycled glass fine aggregate (RGS) causes an alkali-silica reaction (ASR). Various supplementary cementitious materials (SCMs) can reduce ASR expansion of RGS. In this study, the mechanical properties after ASR of RGS mortar mixed with SCMs was evaluated. It was confirmed that the RGS mortar mixed with SCMs decreased ASR expansion. However, the mechanical properties after ASR decreased as reaction days increased. This is because ASR gel was formed inside the microcracks that existed in RGS. Therefore, the ASR gel inside the RGS destroyed the RGS and reduce the mechanical properties.

Keywords: recycled glass fine aggregate, mortar, ASR, expansion, mechanical properties

1. INTRODUCTION

Currently, environmental problems about waste glass emitted from cities are occurring in Korea, Hong Kong, and European countries etc. Since recycling of waste glass is possible only when the color is separated and not broken, the recycling ratio remains at about 60~70% [1]. Also, in Korea, the production of natural fine aggregates has decreased because it destroys the environment and eco systems. To solve this problem, research is being conducted to develop various recycled fine aggregates like crushed fine aggregate.

In order to solve the environmental problems caused by waste glass and natural fine aggregates (NS) at the same time, a recycled glass sand (RGS) was developed in which waste glass was crushed into the particle size of fine aggregates [2-4]. However, various researchers have reported that because RGS has a smooth surface, the cement matrix and adhesion are reduced. As a result, the mechanical properties were reduced. In addition, it is reported that RGS occurred the ASR expansion due to composed of amorphous silica [5-9].

Various studies have been conducted to prevent mechanical properties decrease and ASR of RGS. Among these studies, a method of replacing cement with mineral admixtures (and supplementary cementitious materials, SCMs) has been performed. SCMs such as fly ash (FA) and granulated blast furnace slag (BS) can improve the microstructure of the cement matrix to increase the mechanical properties. Through this, it was found that the decrease in the mechanical properties of the RGS mortar can be improved. In addition, it has been reported that SCMs can lower the pH and porosity of the cement matrix, thereby reducing ASR expansion of RGS mortar and concrete [10-13].

Meanwhile, reactive aggregates such as Opal, Chaledony etc, generate ASR expansion. ASR expansion of reactive aggregates causes cracks in the structure of mortar or concrete. This crack dramatically reduces the mechanical properties and durability of concrete and mortar. Therefore, many studies have been conducted on mechanical properties under ASR conditions for various reactive aggregates [14-18].

The ASR of the reactive aggregate form ASR gel, and the gel expands by absorbing moisture. It has been reported that this expansion of the ASR gel decreases the elastic modulus and strength of mortar and concrete. [14-16] Also, it has been reported that ASR expansion and mechanical properties after ASR are affected by the type and shape of reactive aggregates and the composition of ASR gel [17].

Therefore, studies on the expansion and residual mechanical properties under ASR of concrete or mortar with reactive aggregate should be conducted. In the case of RGS, mechanical properties after ASR are expected to be significantly degraded due to large ASR expansion. However, research on the mechanical properties after ASR of RGS is insufficient.

Also, due to the using of SCMs reduced the ASR expansion of RGS, it is expected to prevent decrease of mechanical properties after ASR. However, research about mechanical properties after ASR of RGS is insufficient, and it is essential to review for proper use of RGS and SCMs.

Therefore, in this study, the basic mechanical properties, ASR expansion and mechanical properties after ASR of RGS mortar mixed with SCMs were evaluated. Through this, the effect of SCMs on ASR expansion behavior and mechanical properties of RGS mortar was analyzed and also the appropriate use of SCMs were analyzed for control the ASR and mechanical properties decrease.

*1 Doctoral Course, Dept. of Architecture Engineering, Chnugnam National Univ., Korea, JCI Member
*2 Prof., Dept. of Architecture Engineering, Chnugnam National Univ., Korea, JCI Member
*3 Associate Prof., Dept. of Architecture Engineering, Chnugnam National Univ., Korea, JCI Member

Table 1 Experimental plan and mix proportion

Type*1	W/B	Unit Weight (kg/m³)						
		Water	Binder				NS	RGS
			Cement	FA	SF	GGBS		
NS	0.5	256	512				1536	
RGS		256	512					1536
RGS_FA		256	409.6	102.4				1536
RGS_SF		256	460.8		51.2			1536
RGS_BS		256	307.2			204.8		1536

*1: NS: Natural fine aggregate, RGS : Recycled glass fine aggregate
FA: Fly ash(F type), SF : Silica fume, BS : Ground Granulated Blast-furnace Slag

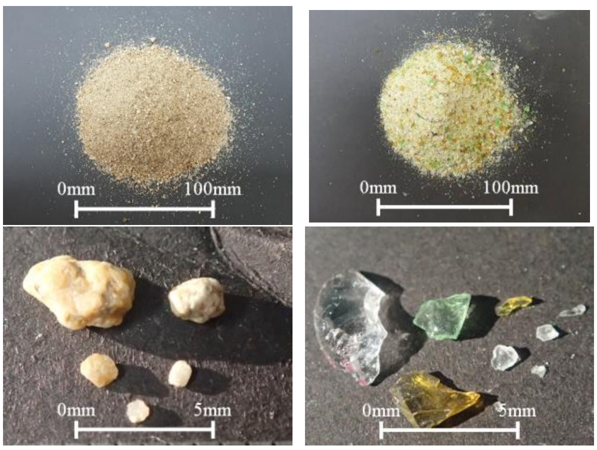
2. EXPERIMENTAL PLAN AND METHOD

2.1 Mix proportion and materials

Table 1 shows the mix proportions table of this study. For RGS mortar, the water/binder ratio(W/B) was set to 0.5, and the fine aggregate/binder ratio(S/B) was set to 3. The ASR expansion specimen was set to 0.47 for W/C and 2.25 for S/C according to ASTM C 1260.

Table 2 Physical properties of the used materials

Materi-als	Mechanical Properties
Cement	Ordinary Portland Cement; Density: 3.15g/cm³; Fineness: 3,200cm²/g
FA	Density: 2.20g/cm³; Fineness: 3,940cm²/g Type: F; Median particle size(μm): 10~100
SF	Density: 2.34g/cm³; Fineness: 200,000cm²/g Median particle size(μm): 0.1~0.3
BS	Density: 2.91g/cm³; Fineness: 4,580cm²/g Median particle size(μm): 12~16
NS	Density: 2.54g/cm³; Fineness modulus: 2.53 Water absorption: 1.6%
RGS	Density: 2.45g/cm³; Fineness modulus: 2.95 Water absorption: 0.4%



(a) NS (b) RGS

Fig.1 Image of the used fine aggregate

FA, Silica fume (SF), and BS were used to evaluate the effect of SCMs. The replacement ratio of SCMs was set based on previous study. Cement replacement ratio was 20% for FA, 10% for SF, and 40% for BS [13].

Table 2 shows the physical properties of the materials used in this study. The cement was ordinary portland cement. Type F FA was used, which is effective in controlling ASR. SF has the smallest particle size, so the unit of particles is micrometer, and the fineness of SF is very high at 200,000. BS was used with a density of 2.91 g/cm³ and fineness of 4,580cm²/g. Meanwhile, the fine aggregates used in this study are natural fine aggregates (NS) and RGS. RGS is a soda lime glass bottle crushed into the particle size of the fine aggregate through a roll crusher. GS was found to have a slightly lower density than NS, and the water absorption ratio was close to zero. Fig. 1 and 2 show the image and particle size distribution curves of NS and RGS. RGS used a mixture of brown, green, and transparent crushed glass bottle in the same ratio. RGS has a sharper shape than NS and has a smooth surface. Both aggregates satisfied the standard particle size distribution curve of fine aggregates.

2.2 Test methods

Flow(ASTM C1437) and air content(EN 1015-7) of mortar were measured to evaluate the basic properties of RGS mortar mixed with SCMs. The flexural and

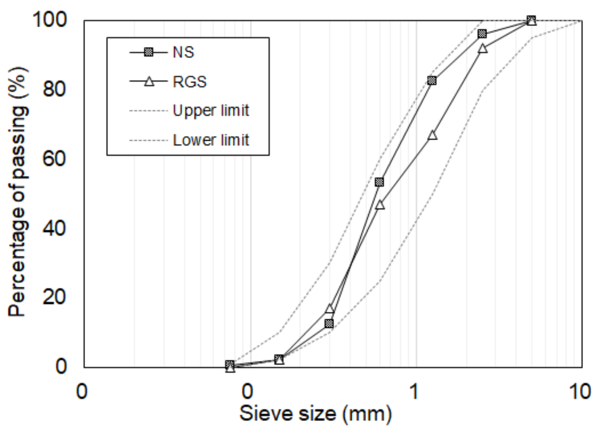


Fig.2 Particle size distribution of used fine aggregate

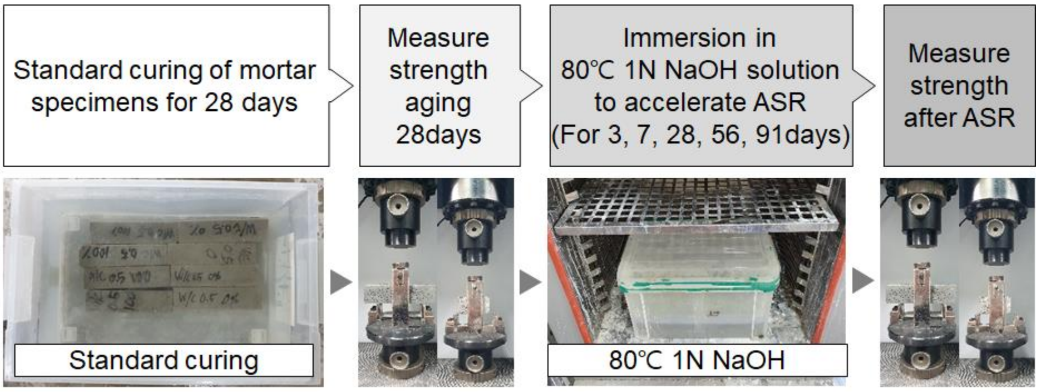


Fig. 3 The method of mechanical properties under ASR conditions

compressive strength of mortar were measured.

To evaluate ASR expansion, it was measured through ASTM C1260 and C1567 methods. In order to accelerate ASR, the mortar specimen was immersed in a 80°C 1N NaOH solution and the length change rate was measured.

To evaluate mechanical properties after ASR, as shown in Fig. 3, a mortar specimen for mechanical properties was immersed at 80°C 1N NaOH solution, and flexural and compressive strength were measured at 3, 7, 28, 56, and 91 days. In addition, when measuring strength, the change in length of the mortar specimen was measured.

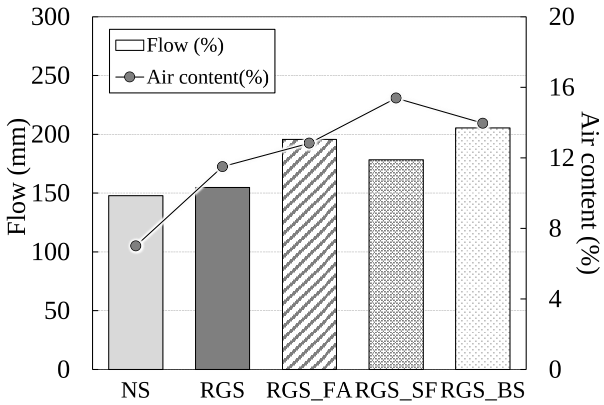


Fig.4 The results of flow and air content

3. RESULTS AND DISCUSSIONS

3.1 Flow and air content

Fig. 4 shows the results of flow and air content of RGS mortar mixed with SCMs. It was confirmed that RGS increased flow and air content compared to NS. This is believed to have increased due to the water absorption rate of RGS close to zero and the long and elongated shape of RGS. In the case of mixing SCMs, flow and air content increased significantly due to the workability improvement effect.

3.2 Mechanical properties

Fig. 5 shows the results of the mechanical properties of RGS mortar with SCMs. Similar to previous studies, RGS has significantly reduced flexural and compressive strength compared to NS mortar [5]. This is because the adhesion to the cement matrix was decreased due to the smooth surface of the RGS and increased the air content of mortar (Fig. 4).

In the case of RGS_FA mortar, flexural and compressive strength were lower than that of RGS mortar due to the cement dilution effect. In the case of RGS_SF mortar, flexural and compressive strength were higher than that of RGS mortar due to fast reactivity of micro particles size of SF. In the case of RGS_BS, the flexural and compressive strength is higher than that of RGS_FA due to the latent hydraulic. However, due to the relatively slow reaction rate, the mechanical properties were similar to that of RGS mortar.

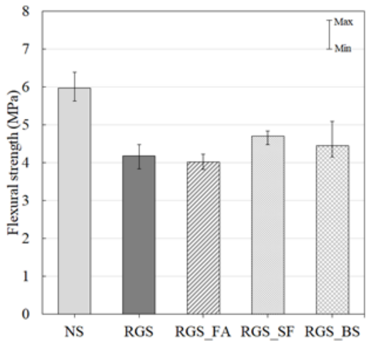
It was confirmed that RGS reduced the flexural and compressive strength of mortar similar to previous studies. However, in the case of using SCMs, the decrease mechanical properties of RGS was not significantly improved. FA has rather reduced the mechanical properties due to its slow reactivity. This is because FA has a very large particle size and is slow to react. SF was found to improve the decrease strength compared to FA. SF showed the effects of fast reactivity due to micro particle size. As a result, the strength of RGS_SF mortar was higher than that of RGS and RGS_FA, BS mortar.

3.3 ASR expansion

Fig. 6 shows the results of ASR expansion of RGS mortar according to type of SCMs. Fig. 6 is the result of ASR expansion test based on ASTM C 1260 and 1567.

As shown in Fig. 6, the amount of ASR expansion in RGS mortar exceeded 0.1% at 14 days based on ASTM C 1260. The RGS mortar showed an ASR expansion amount that was about 3 times larger than that of the NS test specimen. Expansion rate of 0.3% means very harmful ASR expansion. ASR expansion increased until 28 days, expanding by about 0.7%.

However, RGS_FA, SF, BS mortars significantly reduced the ASR expansion. The amount of expansion was less than 0.1% in 14 days. Through this, it was confirmed that the SCMs can reduce the ASR expansion of



(a) Flexural strength

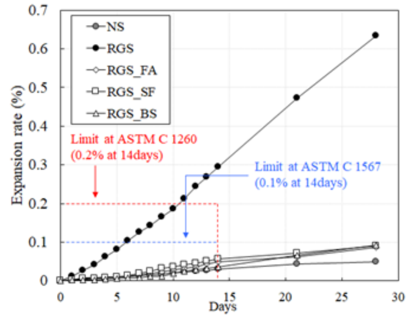


Fig.6 ASR expansion of mortar bar of ASTM C1260

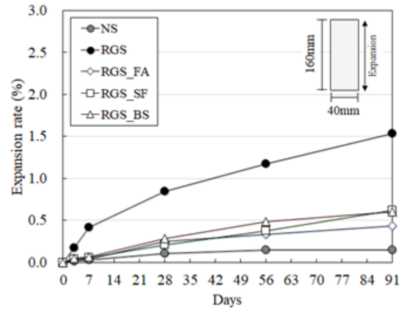
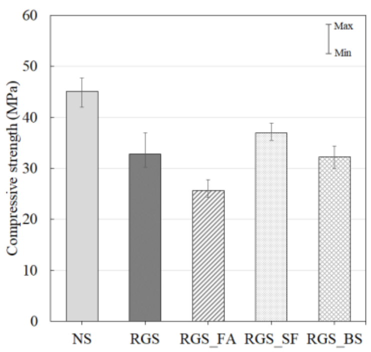
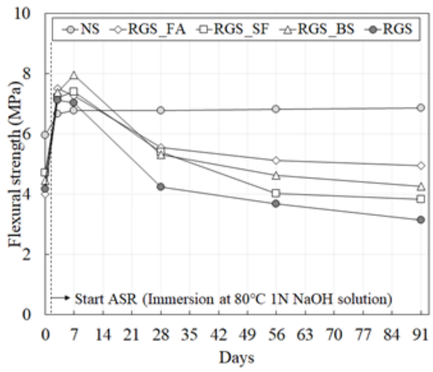


Fig.7 ASR expansion of mortar bar for mechanical properties

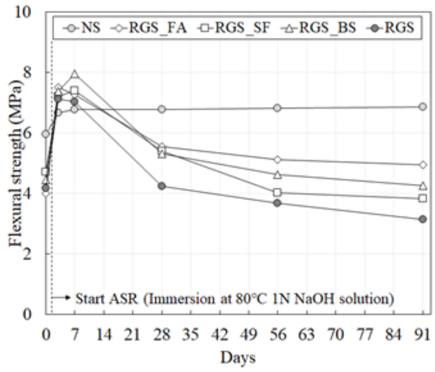


(b) Compressive strength

Fig.5 Mechanical properties



(a) Flexural strength



(b) Compressive strength

Fig.8 Mechanical properties after ASR

the RGS. SCMs reduce the pH and alkalinity of the cement matrix and improve the micro structure, so it is believed that ASR expansion was reduced. In accordance with ASTM C1567, the amount of expansion did not exceed 0.1% after 14 days of ASR. Therefore, it is determined that mixing SCMs does not cause harmful ASR expansion of RGS.

3.4 Mechanical properties after ASR

As shown in Fig. 7, test specimens for the mechanical test after ASR showed a similar expansion rate with ASR test (Fig. 6) in accordance with ASTM standard. The mortar mixed with SCMs showed a decrease in ASR expansion compared to RGS mortar.

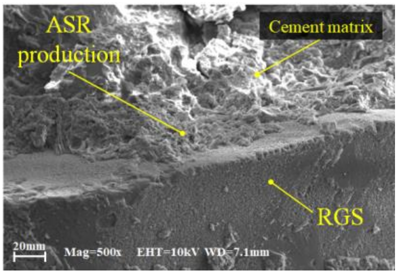
The results of mechanical properties after ASR are shown in Fig. 8. As shown in Fig. 8-(a) and (b), the residual flexural and compressive strength did not decrease until about 7 days after ASR occurred. The flexural strength increased significantly after 7 days of the ASR. The compressive strength also increased. This is believed to be due to the reaction between the alkali of the cement matrix and the RGS interface in the early ASR to form ASR gel as shown in Fig. 9-(a). It is believed that the formed ASR gel increased adhesion and microstructure by improving the ITZ present in the RGS interface and the cement matrix. Previous studies also reported that ASR of reactive aggregates slightly increased mechanical properties by improving microstructure and ITZ due to gel formation [18].

However, after the initial of ASR, flexural and compressive strength after ASR decreased at both RGS mortar and RGS_FA, SF, BS. In the case of RGS mortar, As shown in Fig. 9-(b), After initial ASR, the excessive ASR expansion was occurred. Due to that, it is confirmed that large and small cracks and destruction occurred in the cement matrix.

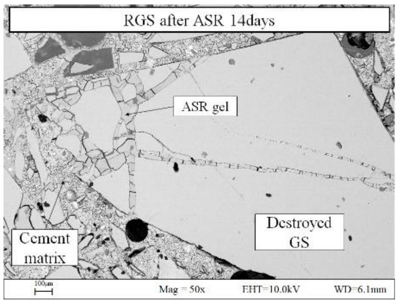
Meanwhile, in case of the RGS_FA, SF, BS, as shown in Fig. 7-(b), it was found that the ASR expansion rate was not large and reduced. In initial ASR, the mechanical properties after ASR was increased similar with RGS mortar. In case of the RGS_FA, SF, BS, as it was immersed in a high-temperature NaOH solution, there is a possibility that the strength may be increased due to the reaction of unreacted SCMs.

However, mechanical properties after ASR was decreased after ASR 14 days. It was expected that mechanical properties after ASR would be not decreased compared to RGS mortar because ASR expansion amount was reduced by mixing SCMs. However, RGS_FA, SF, and BS mortar also decreased in flexural and compressive strength similar to RGS mortar.

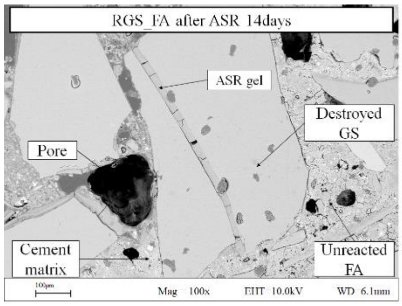
As shown in Fig. 10-(b), (c), and (d), even in RGS mortar using SCMs, ASR gel was formed inside RGS, and the RGS was destroyed similar with RGS mortar without SCMs and Fig. 10-(a). This is because micro cracks were occurred in the RGS during the crushing process. Previous studies have also reported that ASR occurs on the surface of aggregates, but ASR occur in microcracks existing in aggregates [5]. Therefore, even though SCMs are mixed, ASR gel is formed inside the



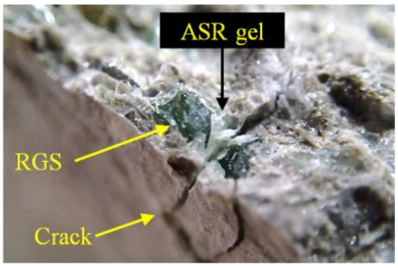
(a) Initial ASR



(a) RGS mortar

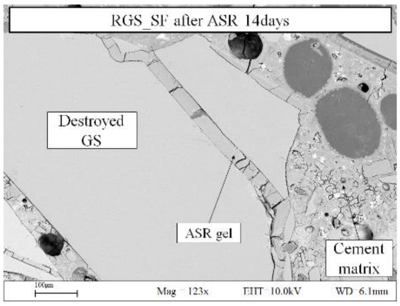


(b) RGS_FA mortar

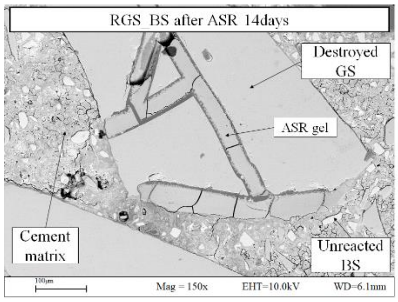


(b) Later ASR

Fig.9 Image of ITZ and RGS ASR gel after ASR



(c) RGS_SF mortar



(d) RGS_BS mortar

Fig.10 Backscattered electron image of RGS after ASR

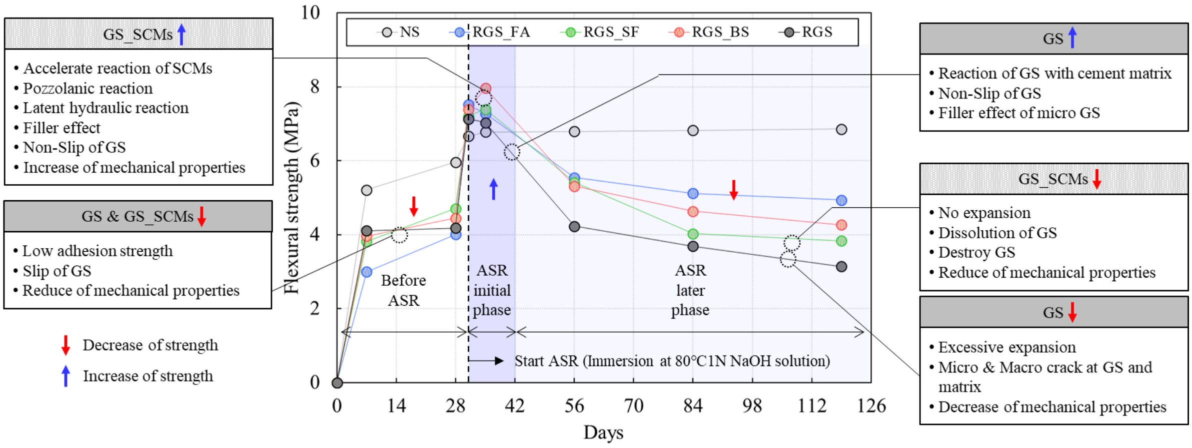


Fig.11The schematic of mechanical properties behavior under ASR condition of RGS mortar

RGS, and the aggregate is destroyed, resulting in a decrease in mechanical properties after ASR.

Fig. 11 shows the mechanical properties after ASR and the mechanism to each section according to the ASR days of RGS mortar mixed with SCMs. In this study, it was confirmed that RGS mortar mixed with and without SCMs, mechanical properties behavior under ASR was similar, however, it is thought that the cause of the behavior was different. In the initial of ASR, RGS without SCMs temporarily increase the mechanical properties due to the improvement of ITZ and microstructure by forming the ASR gel between RGS and cement matrix. In case of RGS mortar with SCMs, it is judged that the residual mechanical properties of RGS mortar mixed with SCMs are temporarily increased due to the pozzolanic reaction and the latent hydraulic of unreacted SCMs particle.

However, in the later phase of ASR, the micro and macro cracks was occurred in the RGS mortar without SCMs specimen. It was due to excessive ASR expansion of RGS, resulting in a dramatically decrease in residual mechanical properties.

However, in case of the RGS mortar mixed with SCMs, although the ASR expansion was not large, the residual mechanical properties were reduced. This is because ASR was occurred inside the micro cracks in RGS. Due to these cracks, RGS was destroyed and dissolved, decreasing the hardness of the RGS.

Meanwhile, according to existing studies, it is judged that ASR expansion of RGS can be reduced by using SCMs. This is based only on the expansion rate criteria according to ASTM C 1260 and 1567. In this study, the use of SCMs did not cause harmful ASR expansion according to ASTM criteria. However, the mechanical properties after ASR of RGS mortar with SCMs was decreased. Through this, it is judged that it will be limitations in evaluating the stability of RGS after ASR only based on the expansion rate based on ASTM.

4. CONCLUSIONS

This study evaluated the mechanical properties and ASR, residual mechanical properties after ASR of RGS mortar with SCMs and without SCMs. The conclusion is as follows.

(1) As a result of evaluating the mechanical properties of RGS mortar mixed with SCMs, FA had a lower strength than RGS mortar due to the cement dilution effect. However, SF have improved in strength compared to RGS mortar due to relatively fast reactivity of SF.
(2) The RGS occurred harmful ASR expansion. However, when SCMs were mixed, ASR expansion was significantly reduced. This is because the reduction of pH and alkalinity in the cement matrix and influenced the reduction expansion of ASR gel.
(3) Mechanical properties after ASR of the RGS mortar without SCMs was decreased due to excessive ASR expansion. However, RGS mortar with SCMs showed a long-term decrease in residual mechanical properties after ASR due to form the ASR gel in micro cracks in the RGS.
(4) Through this, it is considered that there is a limit to evaluating the ASR stability of RGS through only the amount of ASR expansion by ASTM C 1260 and 1567. Therefore, this study used only the ASR acceleration method, but in future studies, long-term performance evaluation is required through natural exposure ASR experiments.

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