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≫ 研究論文 ≪

A Study on the Application of Recycled Fine Aggregate under Sulfate Environment†

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Abstract

The report of an investigation into the performance of mortar specimens made with recycled fine aggregate (RA) exposed to sodium sulfate solution for 360 days is presented in this paper. Mechanical properties of mortar specimens such as visual examination, compressive strength, expansion and mass loss were periodically monitored. From the test results, it was found that mortar specimens with higher replacement levels of RA exhibited poor performance in sodium sulfate solution. However, compared to mortar specimens without RA, those with lower replacement levels of RA (up to 50% by mass) was more resistant to sulfate attack. Through the x-ray diffraction analysis, it was confirmed that the main products causing sulfate deterioration in RA mortar specimens were the formation of gypsum and thaumasite.

Key words : Recycled fine aggregate, Sulfate attack, Compressive strength, Expansion, Mass loss

1. Introduction

A huge quantity of construction and demolition waste is produced every year in Korea. The disposal of waste has become a severe social and environmental problem. The possibility of recycling of waste from the construction industry is of increasing importance[1]. In addition to the environmental benefits in reducing the demand on land for disposing the waste, the use of the recycling waste for the concrete materials can help to conserve natural materials and to reduce the cost of waste treatment prior to disposal.

In fact, based on a great number of studies and field-applications, concrete has been recycled successfully with a viewpoint of reducing energy consumption in the developed countries. Furthermore, many research studies are carried out on the use of recycled aggregate in concrete in an attempt to understand the properties of concrete containing recycled aggregate[2,3].

However, most of the studies are focused on the mechanical properties of the resulting concrete. Limited works are carried out on the understanding of the durability. Especially, studies on the sulfate resistance of mortars or concretes made with recycled aggregates are very seldom.

The characteristics of ITZ and pore structures in concrete with recycled aggregate are significantly different compared with those in concrete with natural aggregate[4]. These may arise some questions for the application of recycled aggregates for concreting materials under sulfate environments.

Thus, it is necessary to assess on the durability of cement matrix containing recycled aggregate subjected to sulfate attack, and to verify the corresponding deterioration mechanism.

This study presents an investigation on the sulfate resistance of mortar specimens partially or fully replaced with recycled fine aggregate produced in Korea. In particular, it was focused on the effect of replacement levels of recycled fine aggregate.

2. Experimental

2.1. Materials

2.1.1 Cement

The cement used in this work was a commercial grade ASTM C 150 Type I portland cement, which had been supplied from S cement company in Korea. The specific gravity and specific surface area of the cement

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were 3.13 and 312 m^2/kg, respectively. The chemical composition and minerological compound data, as provided by the cement manufacturer, are listed in Table 1.

2.1.2 Aggregates

Both natural and recycled fine aggregates (RA) were used. Natural fine aggregate was river sand with a fineness modulus of 2.80. RA was obtained from a local industrial source. The detailed properties of both natural and RA are shown in Table 2. The grading test results of fine aggregates are shown in Table 3.

2.1.3. Superplasticizer

To obtain a suitable workability, a polycarbonic acid-based superplasticizing chemical agent was used in all mortar mixtures.

2.1.4 Test solution

Mortar samples were immersed in 5% sodium sulfate solution for 360 days. The test solution was made by dissolving regent-grade chemicals in tap water. For comparison, tap water was used as control solution. Sulfate solution and tap water were maintained at 20±1°C during test period.

2.2. Mixture proportions

The mixture proportions of mortar samples tested were presented in Table 4. The replacement levels of RA by mass was determined as 0, 25, 50, 75 and 100%. The water-cement ratio was fixed at 0.45 in all mortar mixtures.

The test specimens consisted of 50 mm cube for compressive strength measurement, and 25×25×285 mm prism for expansion measurement, respectively.

Table 1. Chemical composition and minerological compound of cement

Chemical composition, %									Minerological compound, %			
SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	LOI	C_2S	C_3S	C_3A	C_4AF
20.2	5.8	3.0	63.3	3.4	2.1	0.2	0.3	1.2	16.6	54.9	10.3	9.1

Table 2. Properties of fine aggregates

	Specific gravity	Absorption, %	Adhered mortar, %	Fineness modulus
River sand	2.60	0.80	-	2.80
RA	2.28	10.35	7.10	3.42

Table 3. Sieve analysis of fine aggregate

	Mass passing through sieve, %					
	5 mm	2.5 mm	1.2 mm	0.6 mm	0.3 mm	150 μm
River sand	100	86	68	46	18	2
RA	100	78	46	23	8	3

Table 4. Mixture proportions of mortar

Symbol	Cement, g	Water, g	River sand, g	RA, g
RA0	1,000	450	2,000	-
RA25	1,000	450	1,500	500
RA50	1,000	450	1,000	1,000
RA75	1,000	450	500	1,500
RA100	1,000	450	-	2,000

The mortar specimens were cast in mold and cured under moisture condition for 1 days, after which they were demoulded and moved for water curing. After an additional 6 days curing, all prism mortar specimens and some of cube mortar specimens were transferred to sodium sulfate solution.

2.3. Test techniques

2.3.1 Compressive strength

The 50 mm cube mortar specimens exposed to sodium sulfate solution were used for monitoring the compressive strength at the regular intervals. Companion specimens cured in tap water were also tested at the same exposure period. Compressive strength loss was calculated using the following equation.

$$\textit{Compressive strength loss } (\%) = \frac{(f_{wc}-f_{sc})}{f_{wc}} \times 100$$

where, f_{wc} is the compressive strength of mortar specimens cured in tap water, and f_{sc} is the compressive strength of mortar specimens exposed to sodium sulfate solution.

2.3.2. Expansion

Based on ASTM C 1012, expansion test of the prism mortar specimens was carried out. The expansion measurements were taken on three specimens, and the values averaged.

2.3.3. Mass loss

Prior to measurement of compressive strength of mortar specimens exposed to sulfate solution, mass of the specimens was measured and compared with the initial mass.

2.3.4. X-ray diffraction (XRD)

For XRD analysis, the deteriorated surface parts of RA0 and RA100 mortar specimens were finely ground and sieved through a 74 μm sieve. The XRD was carried out on a x-ray diffractometer using CuKa radiation with a wavelength of 1.54 Å at a voltage of 30 kV, scanning speed of 3°/min. and current of 30 mA.

3. Results and Discussion

3.1. Visual examination

Mortar specimens damaged by sodium sulfate attack were carefully observed to monitor visible signs of deterioration. Fig. 1 shows the visual appearance of the mortar samples with or without RA exposed to sodium sulfate solution for 360 days. From the figure, it was clearly found that the degree of deterioration was significantly different with the replacement levels of RA. The RA0 mortar specimen showed the some cracks at the edges. However, the mortar specimens with 25% and 50% replacement levels of RA showed no visible deterioration up to 360 days, except for little or negligible spalling at the corners. On the other hands, RA75 mortar specimens exhibited some cracks due to sulfate expansion even at the faces in addition to the increased spalling at the corners and edges. The worst damage was observed in the mortar specimen replaced fully with 100% RA. In fact, the deterioration on the mortar specimen started at as early as 91 days. With a further exposure of 300 days, the mortar specimen had completely disintegrated as shown in Fig. 1.

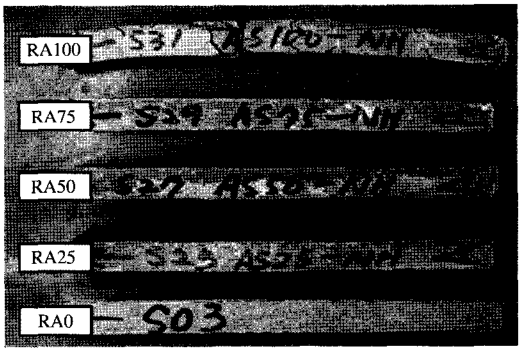

Fig. 1. Mortar specimens exposed to sodium sulfate solution for 360 days.

3.2. Compressive strength

Compressive strength results of mortar specimens cured in tap water are presented in Fig. 2. The 0 day of duration means the curing period after total 7 days of pre-curing, as previously mentioned. The results indicate that the compressive strength values increased with curing period irrespective of the replacement levels of RA. However, there is a trend of development of compressive strength showing the lower strength of mortar specimens with higher replacement levels of RA, although the compressive strength of RA25

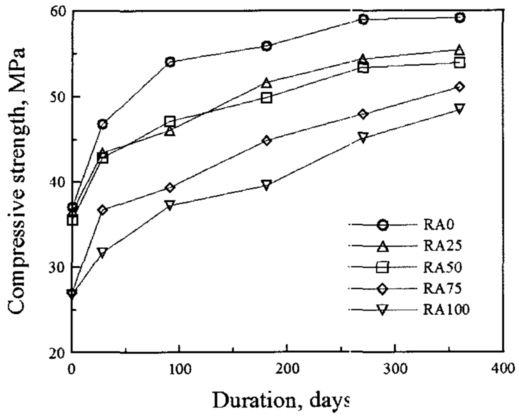

Fig. 2. Compressive strength of mortar specimens cured in tap water.

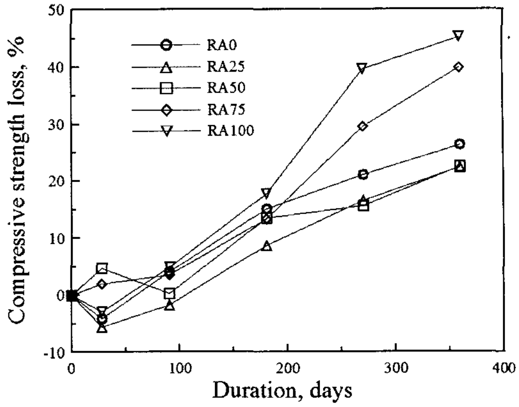

Fig. 4. Compressive strength loss of mortar specimens.

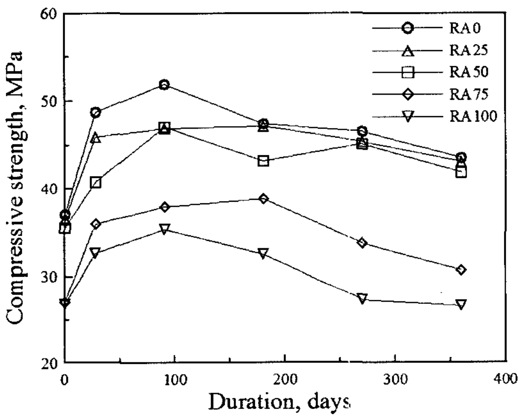

Fig. 3. Compressive strength of mortar specimens exposed to sodium sulfate solution.

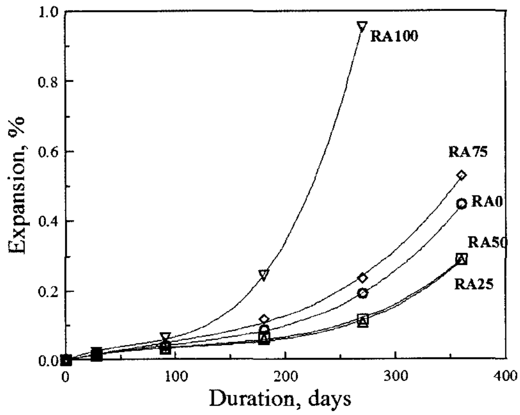

Fig. 5. Expansion of mortar specimens exposed to sodium sulfate solution.

mortar specimens was similar with that of 50% RA.

Fig. 3 shows the results of compressive strength of mortar specimens with different replacement levels of RA exposed to sulfate solution. The results show the mortar specimens suffered the reduction in compressive strength by sodium sulfate attack between the 91 days to 180 days exposure, irrespective of replacement levels of RA. While the ultimate compressive strength values for RA0, RA25 and RA50 mortar specimens were very similar as around 42 MPa after exposure of 360 days, the RA75 and RA100 mortar specimens recorded about 31 and 27 MPa in compressive strength after the same exposure period, respectively.

In order to evaluate quantitatively the deterioration by sulfate attack with respect to compressive strength, the compressive strength loss was calculated using the equation (1) mentioned above, and the results was shown in Fig. 4. It was observed that the compressive strength loss of mortar specimens with higher replacement levels (75% and 100%) of RA was sharply increased after 180 days of exposure. The mortar specimens with lower replacement levels (25% and 50%) of RA exhibited the lower value of compressive strength loss compared with that of RA0 mortar specimens especially after 360 days of exposure. Thus, it can be concluded that the use of the RA up to 50% of replacement levels has a benefit effect on the sulfate resistance with respect to compressive strength loss.

3.3. Expansion

Fig. 5 shows data on the expansion of mortar specimens exposed to sodium sulfate solution. After 91 days of exposure to sodium sulfate solution, there was a sudden increase in expansion for RA100 mortar specimen. The RA100 mortar specimen expanded as high as 0.954% after 270 days of exposure, while RA0 mortar specimen recorded expansion value of 0.192% at the same exposure duration. However, mortar specimens with 25 and 50% replacement levels of RA showed better resistance to sulfate attack with respect to expansion, indicating 0.110% and 0.118% at the exposure duration, respectively. The important observation from the data is that the trend of expansion of mortar specimens is very similar to that of compressive strength loss, which was already mentioned in Fig. 4.

It is believed that the high adhered mortar content and absorption of recycled fine aggregate led to the increased interfacial transition zone (ITZ) in the mortar matrix, and eventually accelerated the degree of sulfate deterioration in the mortar specimens with a higher replacement level of recycled fine aggregate.

3.4. Mass loss

Fig. 6 presents data on mass loss of mortar specimens exposed to sodium sulfate solution for 270 and 360 days, respectively. After 270 days of exposure duration, the mass losses of mortar specimens with lower replacement levels of RA (up to 50%) were the negative values, which mean the mass gains relative to a initial mass, while those with higher replacement levels of RA indicate the positive values. With a longer exposure to 360 days, the mass losses in mortar specimens with higher replacement levels of RA were more pronounced. Especially, the maximum mass loss of 1.4% was noted in RA100 mortar specimen under sodium sulfate attack.

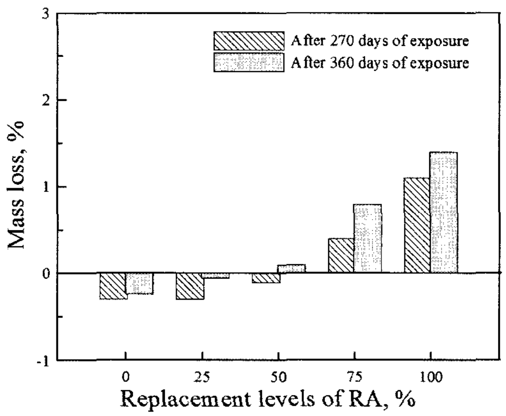

Fig. 6. Mass loss of mortar specimens exposed to sodium sulfate solution.

3.5. X-ray diffraction (XRD)

In order to identify products causing sulfate damage of mortar specimens, XRD was conducted in this work. The tested sample was continuously exposed to sodium sulfate solution for 360 days. From the previous results, it was obvious that the RA100 mortar specimen showed the poor performance in terms of visual deterioration, compressive strength loss and expansion. Therefore, the microstructural investigations were performed on the mortar specimens replaced with 100% RA. Additionally, for comparison of the products formed by sulfate attack, mortar specimen without RA was also examined through XRD.

Fig. 7 shows the XRD patterns of powder samples obtained from the mortar specimens. From the XRD patterns for both RA0 and RA100 mortar specimens, ettringite, thaumasite, gypsum, calcite peaks as well as portlandite peaks were detected. As expected, peak for quartz which was present as fine aggregate in mortar

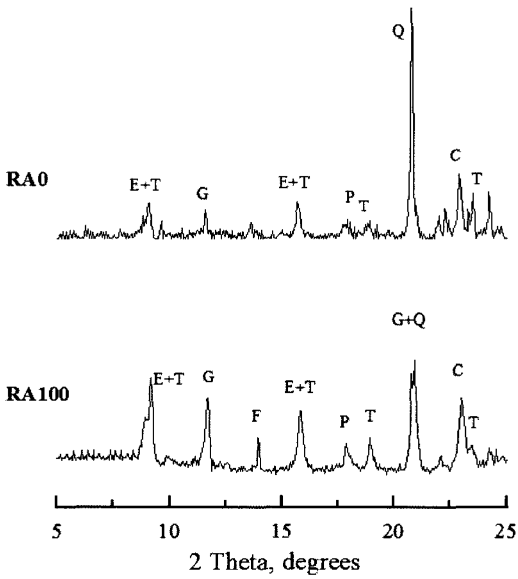

Fig. 7. XRD patterns of mortar specimens exposed to sodium sulfate solution (Note: E-ettringite, T-thaumasite, G-gypsum, P-portlandite, Q-quartz, C-calcite, F-feldspar).

specimens was detected in both sample.

It was found that the main peaks for gypsum were relatively intensive at 11.5° 2θ in RA100 mortar sample compared with those in RA0 mortar sample. Furthermore, relative strong peaks for thaumasite at 9.2, 16.0 and 26.0° 2θ were observed. In fact, both ettringite and thaumasite are present at around 9.2, 16.0° 2θ, although there are small differences in the d-spacing of these peaks in the two minerals[5]. More importantly, it should be noted that the mortar sample were exposed to the solution at room temperature during the test period. Although thaumasite formation is frequently regarded as a low-temperature phenomenon, it can be also detected in the sample exposed to at ambient conditions[6,7].

Thus, it can be concluded that the worst performance of RA100 mortar specimen results from the formation of gypsum and thaumasite rather than the formation of ettringite. However, it is not clear that the formation of thaumasite contributed significantly to the expansion of mortar samples incorporating RA in this scope.

4. Concluding remarks

This paper presents effects of the RA on the resistance of mortar specimens to sodium sulfate attack. Through the tests for 1 year, it was clearly observed that higher replacement levels (over 75%) of RA led to the increased deterioration of mortar specimens by sulfate attack. However, it should be noted that the mortar specimens replaced with RA up to replacement level of 50% showed more resistant compared with those without RA. Additionally, the deterioration mechanism of mortar specimens, especially which were fully replaced with RA, and corresponding products formed by sulfate attack were confirmed through XRD analysis.

Conclusively, the results showed that care should be exercised in designing the replacement level of RA when the resulting concrete is exposed to sulfate-bearing environments.

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